ROCK WALLS IN GLACIER SOURCE AREAS IN PART OF THE HIGHLANDS OF SCOTLAND

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DECLARATION

In accordance with regulation 2.4.15, it is hereby declared that this thesis was composed by myself and that the work is my own.

SUMMARY

Only the rock wall parts of cirques may be consistently defined and delimited. They form the basis of a study of glacier source areas in part of the Scottish Highlands. The rock walls data were abstracted from the recently published photogrammetrically contoured 1:10,000 O.S. maps, with the aid of aerial photographs.

The distribution of cirques in the Highlands has long been attributed to a mean annual precipitation pattern during glaciation similar to that of the present day. From morphometric and trend surface analyses of rock walls a more complex set of relationships emerges. The location, size, shape and aspect and altitudinal distributions are determined by the regional and local rates of glacierization and the neighbouring topography, as well as by a precipitation gradient that was much steeper than at present.

Because of the wide variety in potential for glacierization across the study area erosion rates varied and erosion was not synchronous. In the many cycles of erosion during the Quaternary (as indicated by oceanic core evidence) there were times when the most favourably sited, but often small, rock walls were eroded, but also long periods when these were submerged below major ice bodies and the large rock walls at high altitudes were eroded more slowly. The best-developed rock walls occur on the western islands where they were advantageously placed for precipitation and were seldom over-ridden by external ice.

The azimuths of rock walls are clustered about NE. The contribution of lee effects (precipitation and prevailing wind) to this distribution pattern is considered through the statistical examination of plateaux above rock walls. Plateaux to the SW of rock walls are most consistently correlated with rock wall base altitudes, indicating winds predominantly from that direction. A model of radiation incident on rock walls of various azimuths and angles was constructed to identify the contribution of shading from direct sunlight to glacierization of rock wall sites. This is found to be only locally effective at northerly facing rock walls. In the formerly driest parts of the study area the availibility of plateaux is the more decisive factor in determining rock wall locations and altitudes. It is inferred that the average winter synoptic situation during glacierization was cyclonic, with fronts accompanied by south-easterly to southerly winds lying across the area. Following the passage of each depression winds veered to a prevailing south-westerly direction.

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CHAPTER 1

INTRODUCTION

Models of Glaciation

There are two basic models of glacierization (Bowen, 1978). The role of cirque glacier sources is widely different in each, and hence it is anticipated that the resultant glaciated landscapes will vary. The traditional concept of ice sheet origin and growth involves ice initiated in discrete highland sources. Glacierization is presumed to proceed through convergence and expansion of ice predominantly in a windward direction, reflecting the importance of oceanic precipitation sources in accumulation. Decay is thought to occur by a process of wastage, the final remnants being located in broadly the same places as ice was initiated (Flint, 1957). It is now accepted that major ice masses do not spread from a single highland source area but are due to the convergence of ice from many contemporaneous centres.

An alternative model of extremely rapid growth over a wide area simultaneously has been evolved by Ives *et al*. (1975) to account for the geomorphological evidence and time constraints imposed on the glacierization and deglaciation of parts of Labrador and Baffin Island. This model is referred to as 'instantaneous glacierization'.

In each of these models the role of discrete highland ice sources is different. In the traditional model ice sheets originate through the slow growth of ice from highland sources, the majority of which were cirques. These glaciers supposedly converge and flow outward to form piedmont glaciers and finally ice sheets engulfing the neighbouring lowlands. The ice shed meanwhile migrates away from the dominant moisture source. In marginal conditions cirques are eroded by glaciers in sites peculiarly advantaged for net accumulation and similarly are eroded for lengthy periods during ice sheet build-up.

In instantaneous glacierization, the regional snowline is assumed to be rapidly lowered to the level of much of the land surface. Although small cirque glaciers are formed initially on higher summits, the widespread and rapid expansion of coalescent permanent snowbanks would engulf higher land more rapidly (Ives et al., 1975). In this case cirque glaciers play a limited role both spatially and temporally. Only those remaining above the ice mass are continuously eroded for long periods in each glacial phase, the lower ones being actively excavated for short periods only at the onset of glacial conditions. If the regional snowline is lowered such that the climate is marginally suitable for glacierization, glaciers are not produced in sites with special advantages for net accumulation, but snowbanks form across wide areas. Given sufficient time and accumulation the surface albedo is increased and momentum is added towards rapid and continuous glacierization of the whole surface.

Although these two models were formulated to account for the growth of ice sheets and rely to some extent for their relevance on the land surface topography, their widely different implications for the erosion of cirques under marginal conditions and for the modification of cirque forms during inundation by large ice masses, are obvious. Their differences expose the lack of knowledge surrounding the exact role of cirques as ice sources during glacierization involving the convergence of ice from several cirque sources or ice that has accumulated largely outside the cirque confines. Ice wastes downwards rather than back into original source sites particularly if precipitation decreases and cirques are ultimately occupied by stagnant ice. Since this thesis is concerned with cirque erosion it is glacierization rather than deglaciation that is considered.

Cirques have been used as evidence in studies of the glaciation limit (e.g. Flint and Fidalgo, 1964), in reconstructing former regional snowlines (Porter, 1964) and in inferring former climates (Sale, 1970) often with little regard to their still ill-defined role in glacierization. Much useful work has been done, however, particularly concerning the present distribution of glacierized cirques (Andrews, 1971) and the relationship between climate and glacial environments as inferred from cirque glaciers (Evans, 1974; Williams, 1975).

In the present study, which spans a wide range of terrain, geology and climate, the object is to study cirques as part of the landscape and whole environment in which they were formed and modified, in order (i) to assess under what conditions they were formed, (ii) to assess the contribution they can make to our understanding of the climatic environment, (iii) to infer elements of that climatic environment during phases of glaciation in the Highlands of Scotland and (iv) to relate characteristics of the source areas to other elements of their environment.

The Study Area

The area chosen for this study forms a rectangle some 200km wide and 70km in its north-south extent. The area includes the islands of Skye and Rhum in the west and the Lochnagar plateau and Mt Keen in the east. Latitudinally it includes both the mountains of Kintail and the Cairngorms in the north and the Ben Nevis and Mamore Forest ranges in the south (Fig. 1.1).

The study area is composed of upland topography of great variety from the alpine scenery of the Cuillin ridge on Skye, to

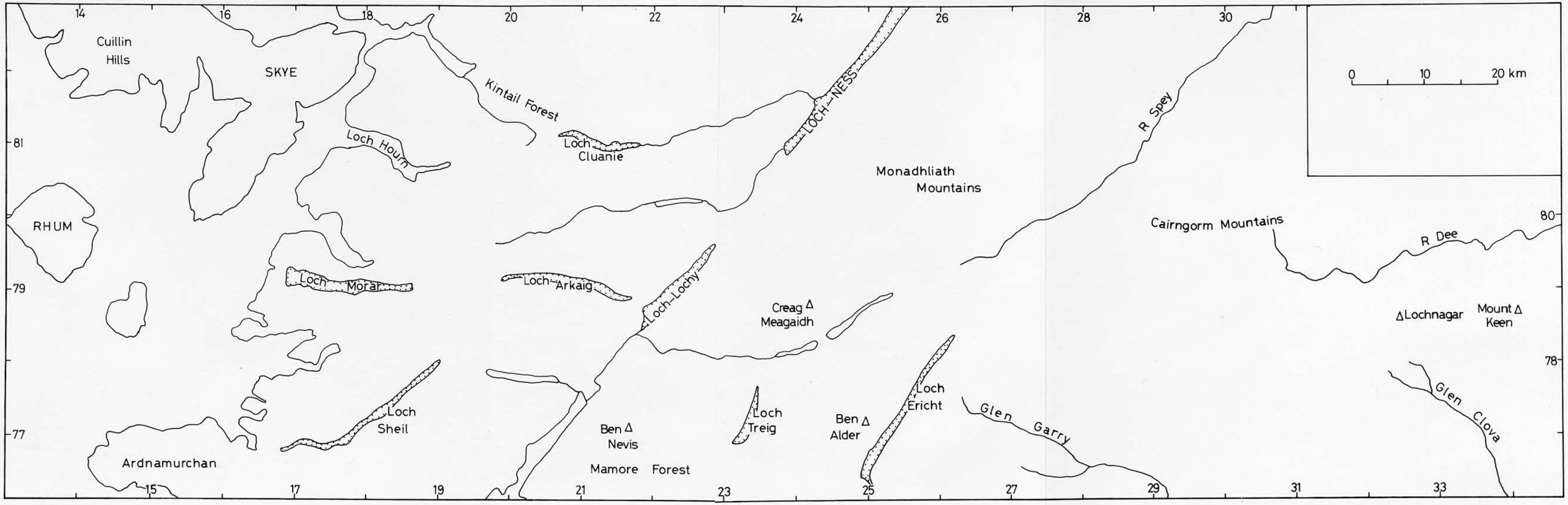


Fig. 1.1 The Study Area

the massive rolling upland plateaux of the east. Topographically the study region may be divided into four main types (Sissons, 1976,p.12). In the western coastal margin of Knoydart and the Ardnamurchan peninsula there is a small area of lowland plateaux with relief rarely greater than 600m but which has been severely glaciated to leave a rocky and irregularly scoured landscape. East of this and covering much of the western Highlands and SW Grampians is an area of mountain ridges and valleys which extend east-west and are deeply dissected by glacial breaching. West of the Great Glen summit altitudes are greatest in the north, many rising to over 800m in the Glen Shiel area. On the Ben Nevis and Mamore Forest ridges of the SW Grampian Highlands summits rise well above 1000m.

East of these dissected mountains there extend broad rolling plateaux of a more massive relief with fewer distinguishable peaks interrupted only by valleys and troughs of Linton's (1963) Icelandic type such as Glen Callater and Glen Muick draining northwards and Glen Esk, Glen Clova and Glen Isla draining south and SE from the eastern Grampian plateau. The plateau altitudes in this area are often as high as the peaks of the mountains farther west and tend to rise towards the north, culminating in the Cairngorm plateau, large parts of which lie above 800m with isolated points rising over 1200m.

Off the west coast of the mainland the mountains of the islands of Skye and Rhum rise in distinct peaks some 800-900m directly from the sea.

Geology

In its geology the study area is also greatly varied. Different rock types and structures have led alternately to variety in the landscape and to uniformity through the similar severity of glacial erosion. The study area may be divided into several broad geological regions, but within each there is a great diversity of rocks and landscape form. The ancient Lewisian gneiss which forms a severely folded and metamorphosed basement to the oldest sedimentary formations of NW Scotland (Watson, 1965) crops out in the extreme NW of the study area at Loch Hourn. Only on Skye are the Late Precambrian Torridonian sediments present, lying unconformably above the Lewisian gneiss. On the mainland, the study area lies almost entirely east of the Moine Thrust and much of it is covered in metamorphosed sedimentary rocks of the Moine series that were laid down at the same general time as the Torridonian sediments (Johnson, 1965a).

The Moinian series is composed of pelitic and psammitic schists, which, where they occur east of the Great Glen, form broad rounded hills and the extensive plateaux of the Monadhliath Mts. Immediately west of the Great Glen the terrain is similar but over a wide area of the West Highlands these are the rocks that form the dissected landscape of impressive peaks, ridges and deep glacial troughs. In these areas the Moinian rocks have been split into three divisions trending NE-SW (Brown et al., 1970). These are:

(i) the Morar division of highly inclined mainly psammitic schists;

(ii) the Glennfinnan division of highly inclined pelitic schists; and

(iii) the Loch Eil division of psammitic rocks known as the flat belt.

In a study of valley pattern modification by watershed breaching during ice sheet erosion in this area, Haynes (1977) considered that the impressive mountains that formed barriers to watershed breaching immediately east of Skye were largely due to the location of the central band of pelitic schists, which occupy the coincident area of relatively high ground.

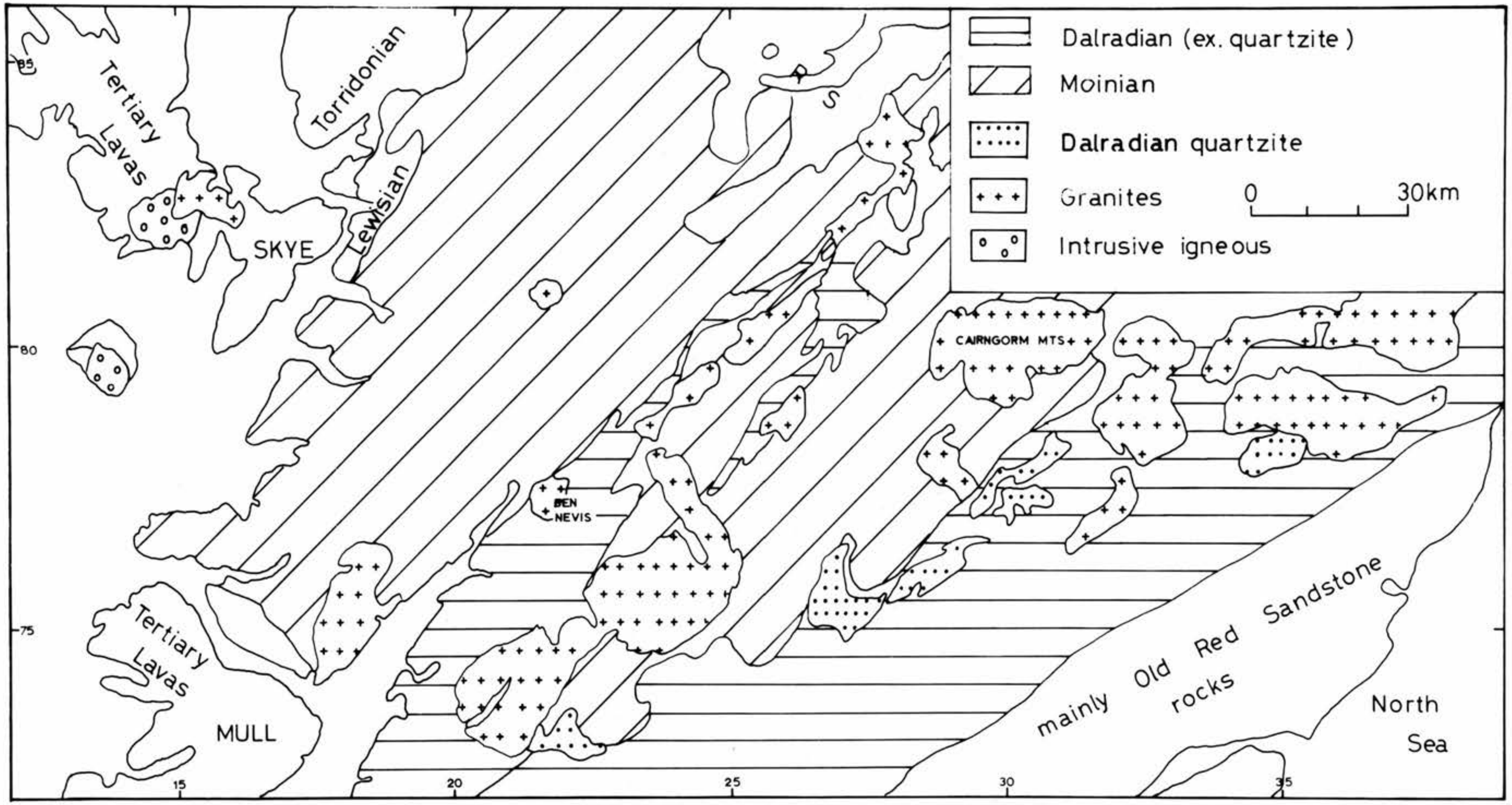


Fig. 1.2 The Geology of the Study Area

In the south and east of the study area the Moinian rocks are overlain by those of the Dalradian, separated from each other by the Iltay Boundary slide (Johnstone et al., 1969). The Dalradian comprises a wide range of metamorphosed sedimentary rocks and forms widely varying landscapes. In the Grampian Highlands much of the rolling plateaux are composed of Dalradian schists. The highest mountains of the Grampians, which may rise up to 300m above the plateaux, are also formed of Dalradian rock. Dalradian quartzite is extremely resistant to erosion and forms high summits such as Beinn a' Ghlo (1120m). The grits of the Upper Dalradian (Johnson, 1965b) account for other high summits particularly in the SW Grampians.

Both extrusive and intrusive igneous rocks crop out in many parts of the study area. The most significant magmatic rocks intruded before the Tertiary tectonic activity were the Newer Granites and Last Granites, which were emplaced before the sediments of the Dalradian and Moinian Series were folded and metamorphosed (Mercy, 1965). The Newer Granites of the field area consist of granodiorite and a variety of basic and ultrabasic rocks and occur among the Moinian and Dalradian rocks east of the Great Glen (Fig. 1.2). The granites form high land such as the upland plateau of the Cairngorms and also stand above the plateau of Dalradian schists as the imposing cliffs that form the summit of Lochnagar. On the other hand granite forms the inland low basin of Rannoch Moor in the Western Grampians. Since it is uncertain to which of the Granites some complexes belong (e.g. Mercy, 1965) for the purpose of this thesis the Newer and Last Granites are not differentiated and are referred to as the Newer Granites. Dykes related to both Newer and Last Granites occur in the form of swarms trending NE or NNE over much of the Grampian Highlands.

Intrusive complexes of Tertiary igneous rocks occur on the islands of Skye and Rhum. Basic dykes swarm across the

Table 1.1 Air Mass Characteristics over the British Isles

Air Mass	Characteristic
Polar Maritime	Cold in winter, cool in summer. Good visibility. Unstable. Showers.
Returning Polar Maritime	Normal temperatures.Stability increased with distance travelled south before returning NE.
Polar Continental	Very cold in winter,warm in summer. Unstable on windward coasts. Sleet and snow in east, clear skies over western Highlands.
Arctic Continental	Very cold or severe in winter. Unstable, good visibility.Snow showers.
Arctic Maritime	Cold,unstable. Snow showers on windward coasts.
Tropical Maritime	Mild in winter,warm in summer. Stable, poor visibility. Fohn effect in lee of Highlands.
Tropical Continental	Warm in summer. Thunder showers.

after McIntosh and Thom (1969)

Table 1.2 Average Frequency of Weather Types, 1868-1967 %

Weather Type	Year	Dec-Feb	Mar-May	June-Aug	Sept-Nov
Changeable Westerly	25.7	31	19	25	27
Cool North-Westerly	4.7	4	4	6	4
Cool Northerly	7.4	6	9	7	7
Easterly	7.6	7	11	5	7
Mild Southerly	8.6	11	9	6	9
Cyclonic	24.9	23	26	25	25
Anticyclonic	17.5	15	17	21	16

after Lamb (1972a)

The predominance of the unstable westerly type air mass direction is reflected in the distribution of precipitation across the study area at present and is emphasised by orography because of the distribution of high land. For climatic reasons Manley (1959) considered that the amount of precipitatation received during the last advance of ice was little different to that received today. Linton (1959) postulated that the distribution of precipitation has varied little during the formation of the present highland landscape.

Since so much of the weather across the British Isles arrives following a passage across the Atlantic Ocean, the surface temperature of the North Atlantic is critical to synoptic conditions and to long term climatic changes. In historical terms the evidence from oceanic sediments in the North Atlantic indicates that sea surface temperatures have altered rapidly many times. The interplay of the warm surface waters that originate in the subtropics and the cold surface waters from polar regions has been reflected in the

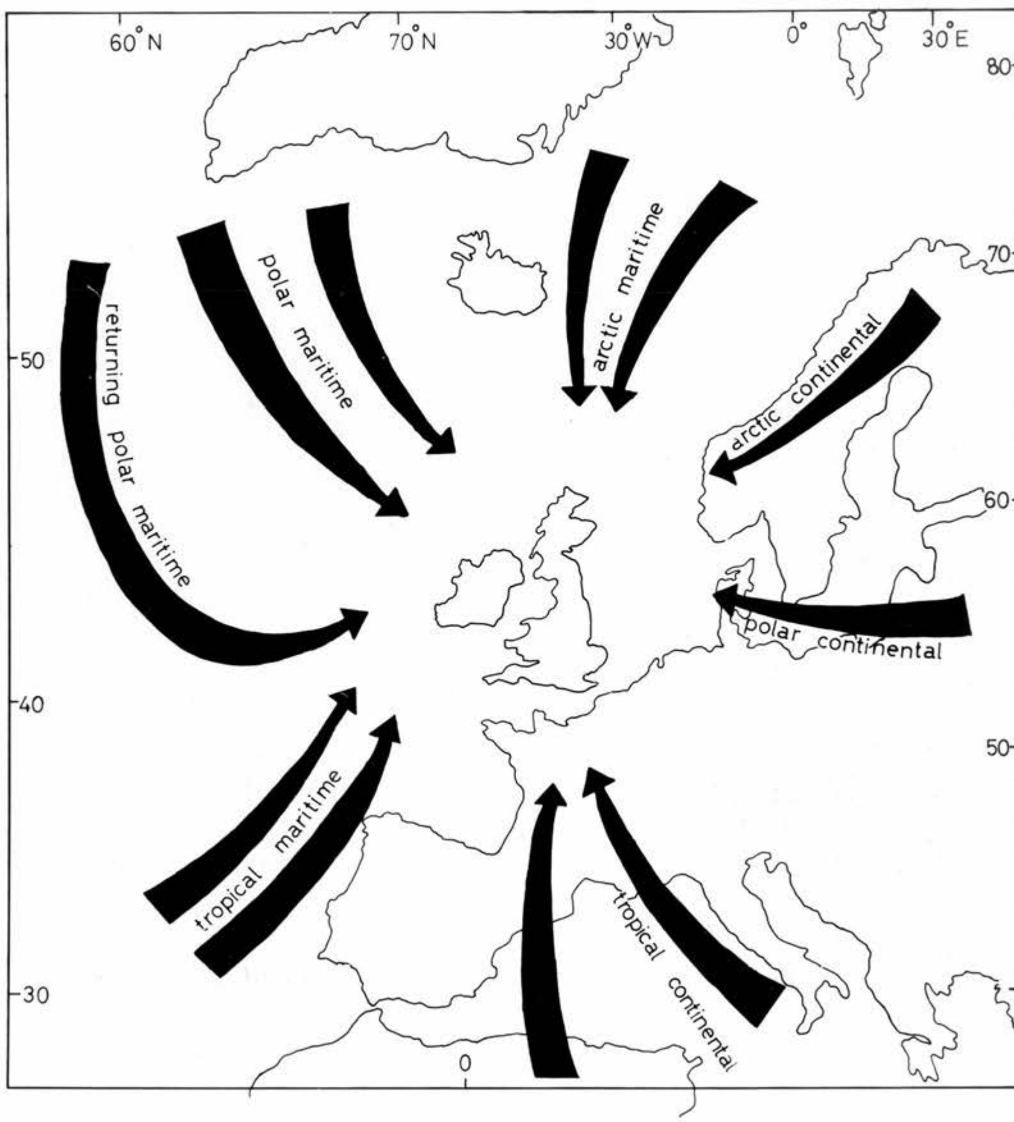


Fig. 1.3 Air Masses affecting the British Isles

growth and decline of ice masses on the continental surface. The range in ocean surface change is large. Ruddiman et al. (1977) calculated that mean summer temperatures in the Atlantic west of Ireland rose 9.8^{0}C during the decline of the last major ice sheet and in the period from 13,700-11,900 B.P. the rise was at a mean rate of 2.6^{0}K(1000yr)$^{-1}$. In geographical terms, surface water masses have migrated across more than 20^{0} of latitude (Ruddiman and McIntyre, 1976). The polar front separating the two water masses moved from its present position along the east coast of Greenland to the latitude of Spain at the ice sheet maximum at 18,000 B.P. (McIntyre and Kipp, 1976).

The range in climate of the study area has been great. At interglacial maxima, mean summer temperatures have been warmer than at present (Shotton, 1977). During the last advance of ice (the Loch Lomond Advance) Sissons (1980) considered that the mean July temperature in the SW Grampians was around 7^{0}C, compared to that presently of 14^{0}C. Winter temperatures are more difficult to assess, but the climate has frequently been more continental than present (Coope and Joachim, 1980). Since fossil frost wedges associated with the last ice advance have been found at sea level (Sissons, 1974a) mean January temperatures can have been no higher than -9^{0}C in the same area during the stadial (Sissons, 1980).

The Glacial Record

Present knowledge of the glacial record is largely based on stratigraphic sequences found at sites confined to the Midlands and southern England. In Scotland since glacial activity has been mostly erosional, evidence for the early events has usually been subsequently destroyed and only evidence for events since the build-up of the last ice sheet is available except in rare instances. The evidence for glacial and interglacial events in the British Isles has been outlined by West (1977). There have been at least three major cold stages since glaciation began during the middle Pleistocene but some stages may be missing from the fragmentary stratigraphic record. Within each cold stage there is evidence for periods of glacial climates alternating with warmer interstadials. Although the exact number and timing of these major events is of no immediate importance to the erosion of cirques in the study area it is significant that there have been many periods of fluctuating climate. This has been corroborated by the complete records inferred from cores taken from the subpolar North Atlantic which indicate many fluctuations in the climate of oceanic NW Europe over at least the last 600,000 years (Ruddiman and McIntyre, 1976).

The early part of the last cold stage, the Devensian, which culminated in the Late-Devensian maximum and was followed by the Loch Lomond Stadial, has been documented mostly from the evidence of fossil beetle assemblages (Coope et al., 1971; Coope, 1975). Evidence for only three interstadials has been found in the British Isles (Shotton, 1977), the Chelford and Upton Warren occurring before the ice sheet maximum and the Lateglacial Interstadial some 5000-7000 years after it. The Chelford Interstadial appeared between two periods of arctic climate (Coope, 1975). Following the Upton Warren Interstadial, at whose thermal peak between 43,000 and 40,000 B.P., temperatures in the south of England were warmer than today (Shotton, 1977), climate became increasingly continental (Coope et al., 1971). Coope (1975) estimated that for a period of some 15,000 years the mean July temperature in the Midlands was around $10^{o}C$ and the mean annual temperature was $-6^{o}C$.

Fossil ice wedges were formed throughout this time in southern England (Watson, 1977).

The build-up to the Late-Devensian ice sheet maximum is considered to have begun at 26,000 B.P. (Mitchell et al., 1973) and the ice reached its maximum extent around 18,000 B.P. The scanty fossil evidence suggests that continentality declined at the close of the Upton Warren Interstadial permitting an increase in precipitation (Coope, 1975). The areal extent of the ice sheet around Scotland is the subject of present debate. Sissons (1976) collated erratic and striae evidence and suggested that the ice sheet was composed of several domes, each centred on high ground, the greatest being that located in the SW Grampians. This largely agreed with Linton (1957) who envisaged two western ice domes, one over the SW Grampians and one over Morven. Ice radiating from the SW Grampians was deflected by the mountain masses of Skye and Mull. Ice moved to the NE, its extent in the NW Cairngorms being recorded by the limit of schist erratics at 800m (Sugden, 1970). No foreign erratics have been found in the SE Grampians which suggests that ice nourished outside this area was prevented from over-running it by the build-up of local ice (Sissons, 1976, p.78). Sissons concluded from the apparent inability of the western ice masses to cover these high easterly plateaux that the maximum surface altitude attained by the ice was restricted to 1500m.

Boulton et al. (1977) employed a theoretical approach to understanding the growth of the Late-Devensian ice sheet and produced a steady-state model of its extent. Constraints were imposed in terms of (i) the maximum extent of the ice sheet (using Charlesworth's (1957) geomorphic evidence), (ii) flow lines abstracted from erratic and till fabric evidence, (iii) climatic snowline estimates, (iv) net accumulation values inferred from estimates of precipitation and temperature and (v) permissible surface temperatures. The map presented of the input of flow lines is at a very small scale. Nowhere in the paper is the scale of the model given (i.e. if the data are generalised over say $10km^2$ or $100km^2$) and inaccuracies are apparent. For example, the flow lines leading away from the SE Grampians are drawn normal to the actual geomorphic evidence. Also, striae may be unreliable, indicating the direction of last ice movements rather than the ice movement when the ice reached a steady-state at its maximum lateral and vertical extent (assuming that it did so).

Nonetheless, using the model, the ice sheet surface was contoured and a maximum summit altitude of over 1800m arrived at. The 1800m contour encloses most of the present field area; it trends NNW across the area from north of the Clyde to Loch Linnhe and parallels the coast at the latitude of Skye. On the east side of the field area it includes the Cairngorms and roughly follows the Highland Boundary southwestwards. This is the first model of its kind for the Late-Devensian ice sheet in the British Isles, and can only be improved as its basic inputs are improved. The discrepancy between the maximum ice altitude produced by Sissons and this model are not great, both indicating that at the glacial maximum the ice stood above the altitudes of the highest mountains.

There were three periods between the ice sheet maximum and the beginning of the Flandrian at 10,000 B.P. Following the maximum there was a period of slow downwastage that may have been due to reduced snowfall (Bishop and Coope, 1977). A rapid amelioration marked the opening of the Lateglacial Interstadial between 13,000 and 14,000 B.P. (Gray and Lowe, 1977) and deglaciation apparently was complete although firm evidence for total deglaciation is lacking. This was followed by the Loch Lomond Stadial, the only post-maximum deterioration in climate that is evident, the glaciers that appeared at this time belonging to the Loch Lomond Advance. The mapped limits of the Loch Lomond Advance glaciers are given by Sissons (1979a) and indicate that ice was most extensive in the W Highlands west of the Great Glen and in the SW Grampians. In the NW Highlands and eastern plateaux ice was sparse. Sissons (1979a) suggested that the ice shed of the large western ice mass attained 850-900m. In areas peripheral to the main ice caps glaciers accumulated in discrete locations. The source locations composing the data of this study generally formed the glacier source areas in the SE Grampians, Skye, the Cairngorms and Rhum (Sissons, 1972; Sissons and Grant, 1972; Sissons, 1977; Sissons, 1979b; Ballantyne and Wain-Hobson, 1980).

From the location and aspect of all glaciers of the Loch Lomond Stadial Sissons (1980) concluded that winds from the SW were most common at that time, but that much snowfall was associated with south to SE air flow preceding atmospheric frontal systems. Mean July temperatures in the Grampians were around 7.0^{o}C and slightly higher in the Lake District (Sissons, 1979c). He calculated that precipitation during the stadial varied greatly across the glaciated area from a maximum similar to present in the SW Grampians (c.f. Manley, 1959) to a postulated minimum of less than 300mm in Speyside (Sissons, 1980). This accords with the pollen evidence of Birks and Mathewes (1978) in Speyside who inferred that the climate was arid from the abundance of Artemsia pollen in the stadial deposits. Variation in precipitation throughout the stadial has also been inferred from pollen assemblages. Caseldine (1980) considered that the pollen present in Stadial deposits at Stormont Loch by Blairgowrie indicate decreases in precipitation as the stadial proceded. At a site in the upper Spey valley Macpherson (1980) inferred that the decrease in precipitation was followed by an increase towards the end of the stadial. Sissons (1980) has speculatively related these types of changes to the movement of the oceanic polar front in the NE Atlantic.

The Erosion of Glacier Source Areas

The climatic and glacial records indicate that a variety of glacial events has occurred in the study area across both time and space. Within the span of the Loch Lomond Stadial the western Highlands (at the latitude of the study area) and the western Grampian mountains were subject to heavy and rapid glacierization, while in the east and NE accumulation was limited. Even during this stage the role of cirque glaciers would therefore be expected to have varied markedly across the study area. Hence the capacity for erosion of each cirque has altered during each period of glaciation and between glaciations. More particularly if it is possible to differentiate between the occurrences of full glaciation and of partial glaciation in time or space there are important implications for the relevance of the models of glacierization discussed above.

In full glaciation mechanisms of both initiation of glaciation from highland sources and instantaneous glacierization would be expected to have occurred. In partial glaciation it is anticipated that highland ice sources are the originators of ice masses. Partial glaciation would appear to be the glacial type in which cirque distribution, altitude, aspect and magnitude are most able to relate to the climatic environment. However, in all interpretations the variation in the role of cirque glacier sources through the cycle of glacierization and deglaciation should be considered. The variety in rock type and topography across the study area is also a factor to be considered in the erosional response of cirques to glacial occupation.

Outline of the Thesis

In this introduction reference has been made to cirques as locations of ice sources. In Chapter 2 an attempt is made to define these objectively and fails. It is found that the most informative and useful part of these source sites is the readily definable rock wall section of the cirque head and side walls, and this is the main object of study in the thesis.

The distribution of former glacier source walls is considered in Chapter 3 in terms of how precipitation would control their location in times and areas of partial glaciation. The influence of other factors that affect their location and erosion during a more massive build-up of ice is sought to explain the distribution fully.

The dimensions of rock walls are analysed in Chapter 4. They are partially explained in terms of the influences on rock wall locations postulated in the previous chapter. Other factors are required to explain them fully and it is concluded that there is not a single direct relationship between the accumulation pattern and rock wall magnitude.

Many writers have used the altitudinal trend of cirques to infer a former pattern of precipitation as well as to place precise limits on past glaciation. In Chapter 5 and 6 the altitudinal distribution of rock walls is considered over small areas (Chapter 5) and as a trend across the study area (Chapter 6). Despite the diversity of glaciation in the field area clear trends are present.

Chapters 7 and 8 focus on the azimuthal distribution of rock walls. Chapter 7 is devoted to patterns in the distribution of aspect both across the study area and altitudinally. In Chapter 8 detailed analysis of the causes of aspect clustering are considered. A model of the influence of insolation on rock walls is evolved and the influence of wind-drifting is considered statistically. Elements of the climate are deduced from the combined results.

Whole cirques, rock walls and their glacierization by Loch Lomond Advance glaciers is the subject of Chapter 9. Information on the lateral extent of cirques increases little the understanding of their role in glacial erosion. The individual nature of the Loch Lomond Advance and its climate is assessed by treating the rock walls of the study area as the total population of accumulation sites during partial glaciation and the sites occupied by Loch Lomond Advance glaciers as a subset of that.

The thesis is concluded (Chapter 10) by presenting a qualitative dynamic model of rock wall glacierization in the study area that relates accumulation of snow and ice through precipitation at rock wall sites, the effects of external ice and submergence by ice and the role of instantaneous glacierization to the distribution of rock walls, their altitudes, aspects and magnitudes. Using this model, elements of the climate during the formation of rock walls are inferred and the timing or rock wall erosion is discussed.

CHAPTER 2

THE MORPHOMETRY OF GLACIER SOURCE WALLS

The Definition of Cirques and Glacier Source Walls

A cirque is a distinctive feature of glacially eroded mountains. It is a steep-sided hollow formed around a mass of glacier ice and firn, more accurately described as a theatre than an amphitheatre, as pointed out by Flint (1957). Although the meaning of a 'well formed cirque' is generally understood, the description is too imprecise for objective study and to cover the full range of morphological features believed to be cirques. Derbyshire (1968) suggested that there is a gradation of cirque forms from deep rock basins to slightly modified valley heads.

In the absence of a universally accepted definition in the literature with which to identify and delimit cirques, authors have traditionally had two courses open to them: to restrict their study to well-defined forms or, to give their own definition with which others are at liberty to disagree. Andrews (1965, p.131) chose the first option in his study of the pattern of cirques in the northern Nain-Okak section of Labrador. He proposed no precise definition and limited his study to

> '. . . well-defined features which are obviously in the category'.

He defended his choice (Evans, 1974, p.102), by showing that with this criterion workers produce substantially the same set of landforms. However, this approach can only be justified under certain circumstances, depending on the objectives of the study and the nature of the field area. If the study is concerned with the evolution of cirques and it is assumed that development is a function of size (Gordon, 1977), the information gathered will only be part of the information required. Where the land surface is deeply dissected by glacial erosion the cirques may not form discrete well-defined features, and the criterion will be difficult to apply. Comparative studies between different mountain areas may be invalid and it is difficult to compare work by different authors because their intuitive 'well-defined cirque' varies. The 'no definition' choice is only admissible where the cirques are situated on otherwise smooth mountain slopes and are independent of each other. However, the study must be restricted to analysis not involving the degree of development of the cirques and the addition of marginal forms should not yield significantly more information. These conditions are rarely met, and the problem of delimiting cirques for morphometric work remains.

The second choice is to define, at the outset, the landform to be studied. The definition must be intuitive, based on the author's knowledge of the landform and the object of the research. This has led to definitions of varying precision in the literature. Trenhaile (1975, p.520) based his study of cirque elevation in the Canadian Cordillera on a landform described as

> ' . . . a hollow with a steep slope, arcuate in plan with a more gently sloping floor'.

A more precise definition was given by Derbyshire (1968, p.119) who suggested that a cirque has three distinctive elements

> '. . . a steep, nearly vertical headwall, a concave floor meeting the headwall in a sharp break of slope, and a lip or threshold at the entrance which may be of bedrock, glacial moraine or both'.

A major result of the varying definitions used is that comparision of results from different authors must be treated with scepticism. An example of the major discrepancies that occur is afforded by the vastly different number of cirques identified by different authors in Scotland. Linton (1959) found 473 Scottish cirques using the 1:63360 Ordnance Survey (Popular Edition) topographic maps, and basing his identification on long field experience. Sale (1970) used the definition given by Flint (1957, p.97) that a cirque is a steep-sided basin roughly semi-circular in plan, cut into a slope by erosion beneath and around a bank of firn or glacier ice. In his map study Sale recorded 876 cirques in Scotland.

A universally acceptable definition of a cirque is required to distinguish cirques readily from non-cirques, delimit them unambiguously, and to distinguish various types of cirques by their formative processes. With such a definition findings by different authors could be directly compared. For such a definition to be useful it has to be comprehensive and operational, being capable of identifying and then delimiting cirques for morphometric analysis. The need for this type of definition was clearly recognized by the British Geomorphological Research Group when they met to consider a definition. The object was to devise a morphological rather than genetic definition of a cirque. The outcome was a broad statement:

> 'A cirque is a hollow, open downstream but bounded upstream by the crest of a steep slope ('headwall') which is arcuate in plan around a more gently-sloping floor. It is <u>glacial</u> if the floor has been affected by glacial erosion, if part of the headwall has developed subaerially, and a drainage divide was located sufficiently close to the top of the headwall for little or none of the ice that fashioned the cirque to have flowed in from outside. (We might tentatively suggest

that part of the headwall exceeds 35^{o}, and
thc floor slopes less than 20^{o}).' (Evans and Cox, 1974, p.151)

The rest of the paper is devoted to discrimination between various types of glacial cirques. Three main criticisms of this attempt at definition are presented here. Arising from these observations the present author proposes an entirely different type of criterion for studying the relationships between the landforms and climate.

The first problem with the above definition is its breadth. In trying to reach a morphological definition to cover every possible cirque form, the broadness itself creates new problems. Almost every niche in a glaciated mountain area around which ice accumulated could be called a glacial cirque. The problem is high-lighted by a study of cirques in the Kintail-Affric-Cannich area of Scotland by Gordon (1977). In this small area Gordon, using a broad working definition similar to that proposed above, identified 231 simple cirques. Many of these are extremely small and poorly developed, approximately one-third having a crest to downstream edge length of less than 400m, the maximum length being 1840m. Gordon considered that many of these small features are secondary cirques but using the definition there is no way to differentiate them. The formation of these niches on cirque walls depends on the size and shape of the initial wall as well as on many other factors. The two types of form should not be considered as one population where the aims of research are to gain understanding of the evolution of cirques.

The second problem is that of delimiting the cirque after initial identification. Here the persistent problem is that of trying to delineate the downstream edge for the requirement that a cirque should have a sill or threshold is not included in the definition. There are several important reasons for this omission but in practice it presents difficulties. Firstly, there are cases where the heads of major glaciated valleys are cirques whose floors merge with the valley floors with no change of gradient (Evans and Cox, 1974). These valley heads certainly have more in common with cirques than with other landforms, although immediately downstream of the headwall the relationship is much less apparent. Secondly, since the role of the threshold in the process of formation of a glacial cirque is not clearly understood, it is unwise to include it as part of the cirque morphology. Thirdly, where a sill is not found in an otherwise well-defined cirque the temptation is to place it at the first downvalley change of floor gradient, no matter how insignificant it appears. In morphometric studies this is particularly important since many measurements commonly made are related to the length of the cirque from headwall to downstream edge. The definition offers no alternative way of defining the downstream boundary. In theoretical terms this is unavoidable but the aim of the BGRG meeting was to provide an operational definition of a cirque. The inability to define clearly the downstream edge suggests a merging with valley glacier processes in certain cirque locations and indicates the difficulties in producing a definition based on the shape rather than process. In not suggesting how to delimit a cirque over part of its perimeter the definition is not satisfactory for morphometric research.

Authors who have considered the problem of definition have had to introduce a criterion for delimiting the downslope boundary. Evans (1974, p.103) only included features where there was a downslope increase in gradient on the downstream edge of the floor, in a study of cirques in British Columbia. Gordon (1977) included six features he called cirque troughs which can only be delimited where they coalesce with other glaciated valleys or major east-west troughs. As he pointed out, these differ markedly in terms of shape from the true cirques he identified. The definition provided by the BGRG seems inoperable in terms of their own aims.

The third criticism of the definition concerns the requirement that glacial cirques should only be fashioned by ice that accumulated within them. This presents difficulties in the case of the many cirques that have been occupied during various stages of glacial history. Goldthwait (1970) found striae and smoothing near the headwall crests of cirques in the New Hampshire range and concluded that this was caused by external ice flowing over the cirque crest. Some Scottish cirques have been entirely overrun by external ice on more than one occasion yet they appear to retain the characteristics of cirques and are well-defined features. The presence of these cirques indicates that, apart from smoothing, a pre-existing cirque is not necessarily radically altered when over-ridden by ice sheets. This is implicitly assumed in the BGRG definition. However, this is not the only form of external ice that may affect cirque morphology. Valley glaciers may be significant in the evolution and hence morphology of perched cirques. Where the cirque glacier is in direct contact with valley ice the downstream portion of the cirque may not be developed comparably with the back wall area. This clause in the definition can only be satisfactorily applied to an undefined rear section of the cirque floor and the complete wall, the upper wall being affected by periglacial processes and the rest by ice moving downslope from it.

The points mentioned above concern the usefulness of the definition as a criterion for identifying cirques and marking their boundaries from the neighbouring hillslopes. The author considers the definition too broad to fulfil the first requirement and incapable of completing the second. It is too optimistic to expect to obtain a morphologically controlled operational definition for identifying the whole group of landforms currently believed to be glacial cirques. This requirement demands a definition based on the processes involved in cirque morphology. It seems probable that these processes merge with slightly different processes downstream of the cirque and it is fruitless to expect to be able to demarcate between them in all cases. The definitive cirque remains in the future.

An alternative solution is offered here. Arising from the above discussion several points are clear. Firstly, glacial cirques base their group identity on the fact that they are formed by local accumulations of snow and glacier ice that always occurs in the back wall area of the cirque during glacial build-up. Secondly, the floor area not adjacent to the back wall is not always pertinent to this function but may be dependent on it, several different longitudinal profiles of this part of the cirque being admissable. Thirdly, it is striking that in almost all cirques, while the downstream edge may or may not be ill-defined, the upstream boundary is identifiable as a distinctive wall made of rock that can be delimited from the area upslope and downslope by sharp breaks of slope. In all the definitions given by previous authors this part of the cirque is consistently defined.

In the present study no definition of a cirque is given but an alternative criterion is used to identify glacial accumulation areas that do not necessarily have all the characteristics of a well-defined cirque, but that are believed to have been formed by the set of erosional processes fundamental to the morphology of the back wall and immediate floor area of a cirque. This is the part or the cirque of any glacial accumulation area which is of greatest importance in considering the role of the whole feature during glaciation, and in understanding its relationships with various climatic parameters. Since the part of the floor that is always controlled by these relationships is not always definable, this study is based on the analysis of rock wall slopes only. Thus, it concentrates on the areas from which ice moved away rather than moved along, and which by implication acted as source walls for cirque or valley glaciers. For the present study this criterion possesses several advantages over an ill-conditioned definition of a cirque:

(i) the population studied comprises all shapes of features from forms which may be components of embryo cirques to well developed source walls;

(ii) the information collected is closely related to the function of glacial accumulation;

(iii) the features are controlled by fewer external parameters since they are quasi-two dimensional rather than three dimensional forms;

(iv) rock walls are easily identified using large scale topographic maps and aerial photographs;

(v) rock wall boundaries are readily defined, the problem of a sill or threshold being precluded;

(vi) a study of rock walls ensures that the last ice present was erosional;

(vii) since the above criterion is objective the definition and measurement of shapes are repeatable;

(viii) by defining the lower edge of the rock wall, a representative altitude of the accumulation area is given.

Morphometry of Glacier Source Walls

The source walls were first identified, then delimited along each edge and finally information was collected from them. In addition to the requirements that source walls be composed of rock and have the appearance of having been plucked, two other requirements were made. Only slopes steeper than 20^{0} and with crestlengths longer than 200m were included. These were considered to be broad limiting values, only one identified slope being discarded on the grounds of slope gradient. A limiting crest length of 200m was chosen because of the scale of maps and aerial photographs from which the data were collected. In fact the crest lengths of source walls are rarely shorter than 600m and it seems that a glacier requires a certain minimum accumulation area. Thus, inclusion of these requirements has not affected the data set substantially.

Rock walls were initially located by scanning stereopairs of aerial photographs at a scale of approximately 1:25,000 using a Casella pocket stereoscope. Because of the ease with which rock walls can be identified the limited magnification provided by such a stereoscope is adequate. Possible rock walls were identified on the photographs by the appearance of steeply sloping bare rock surfaces of a massive, craggy nature. These are quite distinct from other rock slopes on all rock types encountered in the study area. The slope was then located on the new Ordnance Survey 1:10,000 topographic map, which is photogrammetrically contoured at an interval of 10m. In a few areas the 1:10,000 map sheets are not available and the 1:10,560 equivalent sheets with a contour interval of 7.6m were used. Altitudes were taken to the nearest contour when located on the map. The precise location of the rock wall on the map was found with the aid of distinguishable features on both maps and photographs. Since rock walls are quite distinctive features problems were rarely met at this stage.

The boundaries of the rock wall area were marked on the map in three stages with the aid of the aerial photographs. The crestline was drawn where there was a sharp break of slope at the head of the wall. This was nearly always unambiguous but occasionally the photographs showed a gradation from gentle to steep slope from the drainage area above. The crestline was determined as the line on the map where most rapid change occurs. The end slopes were then identified. If the rock wall merged with a vegetated slope the end points of the wall were marked at the junction between the slopes. In many cases the rock wall merged into a valley side wall composed of rock scoured by ice. Here the photographs were examined to find the point where the rock changes from the craggy unevenness of the plucked slope to the smoother valley side which the ice had moved along. In some instances the very top part of the rock wall and the valley sides have been subjected to similar frost shattering, the area below this tending to show the greatest change. Where there was a transition zone between valley side and back wall areas, the the rock wall end point was defined as the midpoint of the zone. Finally, the rock wall base line was drawn on the map. This was defined as the junction between the steep rock slope and the more gently sloping apron. In practice the slope usually comprised two areas, the base of the rock wall being the break of slope dividing the lower section from the apron. This two-part slope is similar to that described by Gilbert (1904) as occurring in the cirques of California. He defined the break of slope between the slope components as the 'schrund line' in accordance with the then popular bergschrund theory of formation of cirques (Johnson, 1904). Where scree masked the lower part of the rock wall the base line was taken as the base of the scree. This may lengthen the slope but is the most objective method of definition. An example of a rock wall delimited in this fashion is shown in Fig. 2.1.

Selection of Rock Wall Descriptors

Several authors have produced comprehensive lists of measurements possible on rock walls and cirques. Andrews and Dugdale (1971) suggested 17 measurements on cirques of which seven are possible on rock walls. Evans (1974) increased the variables to 68 possible for an unoccupied glacial cirque; 29 of these may be made on rock walls. Many of the measurements suggested by Evans are superfluous in terms of the amount of useful information provided and are time consuming to extract

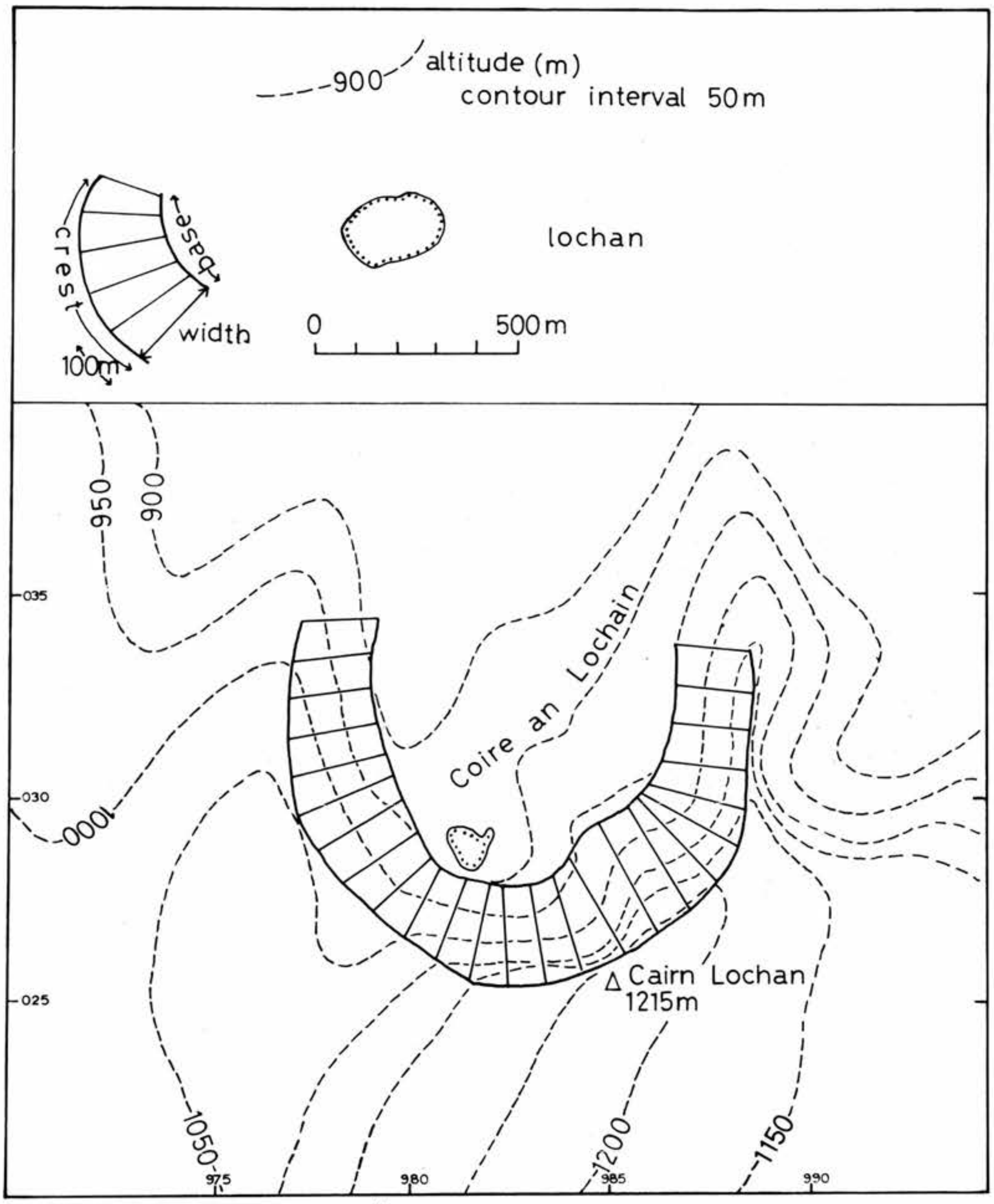


Fig. 2.1 Delimitation of Rock Walls

from the map. The criterion used in this study was to characterise the rock wall simply, with as few useful variables as possible, each providing additional information. Three distinct sets of measurements were necessary: parameters representative of the whole rock wall; measurements abstracted at intervals along the wall; and descriptors derived from these. The full list is provided in Table 2.1.

The first group of descriptors is composed of variables that are representative of the rock wall as a whole. Grid locations were obtained to the nearest 100m, the first and fifth numbers of each reference replacing the normal alphabetic prefix for each 100km grid square. Thus 23477986 replaces NN347986, for ease of computation in locational analysis. Grid references were provided for each end and the midpoint of each rock wall crest line.

The maximum altitude related to the rock wall was arbitrarily taken as the highest point within 500m of the crest line. In practice this is the highest elevation in the vicinity of the rock wall, the only exceptions being in some areas of rolling plateau. In these areas the highest altitude within 500m was assumed to be representative of the maximum plateau altitude.

The length of the crest line was recorded to the nearest 50m. This length was recorded in preference to the base length for two reasons. Firstly, the more arcuate the rock wall the shorter is the base length in relation to the crest length. Thus, for different plan shapes, the crest length varies less than the base length. Secondly, the crest line is always distinct and unambiguous, whereas on some occasions the base line is not so clearly defined along its whole length.

Table 2.1 List of Rock Wall Measurements

A. Measurements Representative of the Whole Wall

Midpoint Grid Reference	8 figure reference, alphabetic code included as first and fifth numbers
Endpoint Grid Reference	as above
Geology	numerical code (Table 2.2)
Maximum surrounding elevation	highest land within 500m, to nearest 10m
Drainge area	area upslope of crest to drainage divide, including incidental downslopes of less than 7.6^{o}
Crest length	length of crest between grid points

B Measurements Along Crest Length

Crest Altitude	to nearest 10m
Base Altitude	"
Width	length of line connecting area and base, to nearest 10m
Aspect	8 classes of 45^{o} intervals centred on N, NE etc.
Amplitude	crest minus base
Gradient	$\tan^{-1}$ (amplitude/width)

C. Mean Descriptors

Mean Crest Altitude
Mean Base Altitude
Mean Width
Mean Amplitude
Mean Gradient

A general geological grouping was employed, each rock wall being assigned to a rock category. These rock types are indicated in Table 2.2. The information was extracted from the newly published 1:50,000 Geological map sheets where available. Elsewhere the six-inch County Series was employed by converting the grid coordinates on the topographic map to their equivalent latitude and longitude values. Where these were unavailable also, the relevant literature was searched. Some rock walls

Table 2.2 Geological Classification

Rock Type	Code
Moinian	01
Dalradian quartzite	02
Dalradian (ex quartzite)	03
Cairngorm granite	04
Lochnagar granite	05
Ben Nevis granite	06
Mount Keen granite	07
Other granites	08
Other igneous rocks	09
Lewisian	10
Unclassified	11

cross rock type boundaries and some cannot be satisfactorily assigned to one category: these were placed in a separate group in the classification. Several previous studies of Scottish cirques have already considered the influence of rock structure on cirque processes (e.g. Haynes, 1968; Gordon, 1977). Since this study is concerned with the processes involved in glacial accumulation as distinct from erosion, a lithological classification of this kind was deemed sufficient.

Accretion of snow against a rock wall may occur due to the blowing of snow off plateau areas above the crest as well as from snow precipitated directly onto the accumulation zone. To consider the importance of this 'drainage area' above the rock wall it was measured and, since falling and newly fallen snow may be blown uphill by strong winds, part of the reverse slope was included. A limiting slope gradient of 7.6^{o} up which snow can be carried was chosen arbitrarily since it is a reasonable value and corresponds to 3mm between successive contours on the Ordnance Survey 1:25,000 topographic maps. Once the total area had been delimited a planimeter was used to measure it. Double counting occurred where several rock walls shared the same drainage areas and was unavoidable because of the nature of the measurement. In some locations, drainage areas were measured for specific directions of snow drift. Plateau areas upslope from the rock wall in several directions were measured. A planimeter was not used here because of inaccuracies in delimiting the components of the plateau areas beyond the normal downslope drainage divide when one specific direction is required. A graphical sampling method was designed to find the total area by summing trapeziums of known breadth, across the whole area. An example is given in Fig 2.2. Assume a plateau to the west is to be evaluated. A set of parallel lines equivalent to 100m apart on the ground is placed across the map oriented west to east. At each intersection of line and the rock wall crest a line is drawn back across the map to where the gradient upslope exceeds 7.6^{o}. Since the length of this line varies rapidly when oriented in slightly different directions the mean length derived from seven measurements at 15^{o} intervals around the direction of interest is taken. In this example the distance to the plateau edge is sampled at each point between NW and SW. Trapezoidal shaped areas were derived by taking the mean of each neighbouring pair of lengths, converting it to ground distance, and multiplying by 100, the breadth in metres of each trapezium. This may appear unnecessarily difficult but it has the capacity to evaluate the plateau area with an upslope component objectively.

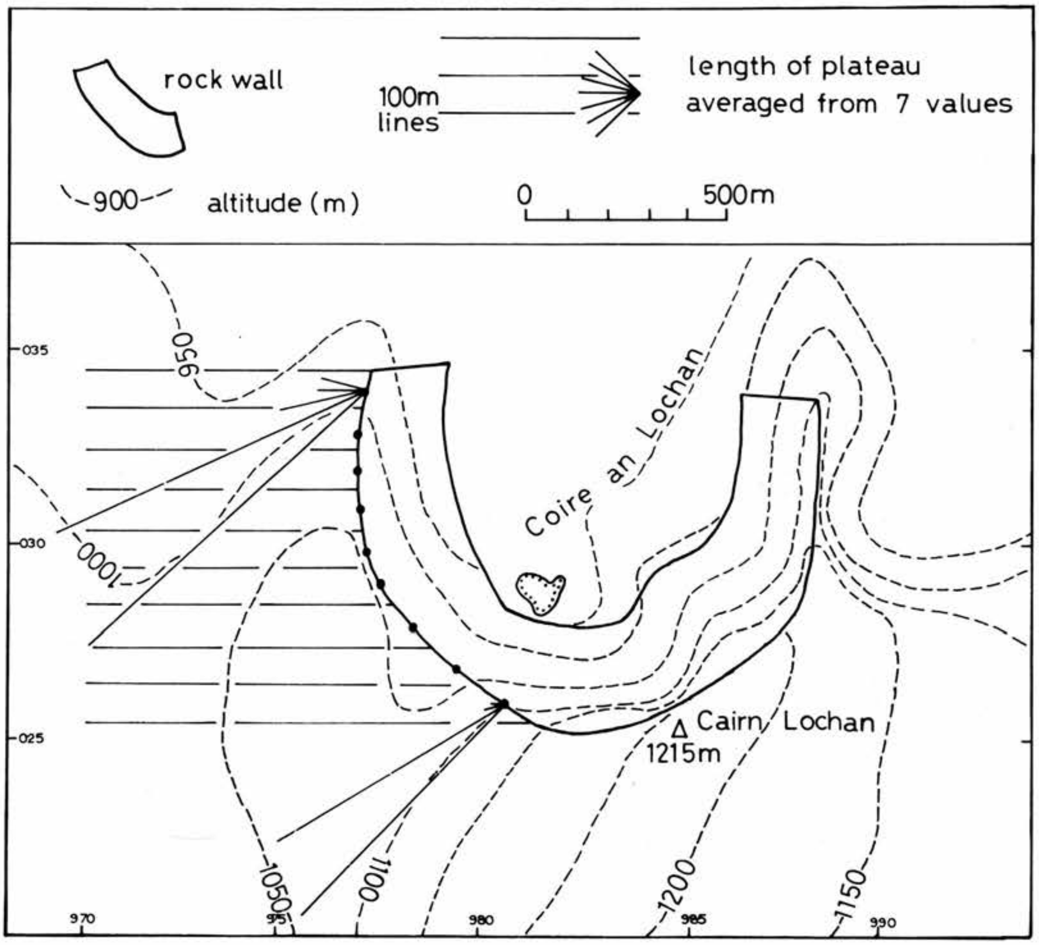


Fig. 2.2 Measurement of Plateau to the west of a Rock Wall

The second group of measurements derived from the map were obtained by abstracting information at 100m intervals along the rock wall crest line. Every 100metres lines were drawn perpendicularly across the map contours to intersect the base line. Simple measurements were made and summarised in Table 2.1. Aspect along each transect from crest to base was given as one of the eight major compass points since the direction downslope may vary considerably. The eight classes were chosen to centre on the eight points of the compass. Thus the NE class contained all transects oriented between N22.5^{o}E and N67.5^{o}E. The aspects were corrected to true north from grid north using the correction factor provided on each map sheet.

The third class of measurements was a set of mean descriptors, computed from the information collected along the rock wall, to characterise each rock wall. In much of the ensuing analysis it is these values that are used in conjunction with the first group of characteristics.

Approach to Analysis

Analysis of the information obtained for each rock wall has been carried out at various areal scales, because variations occur across the field area. In attempting to understand the relationship of rock walls to glacial climate it is necessary to discuss large scale patterns, across which climate may vary considerably and also distributions across small distances where the regional attributes of the climate may not vary greatly. For large scale study the field area has been divided into six regions as shown in Fig 2.3. The regional divides were chosen from topographic divisions which occasionally coincide with major geological divisions, such as the regional border along the Great Glen; each region has been given the name of its dominant mountain group. Where the regional area rather than

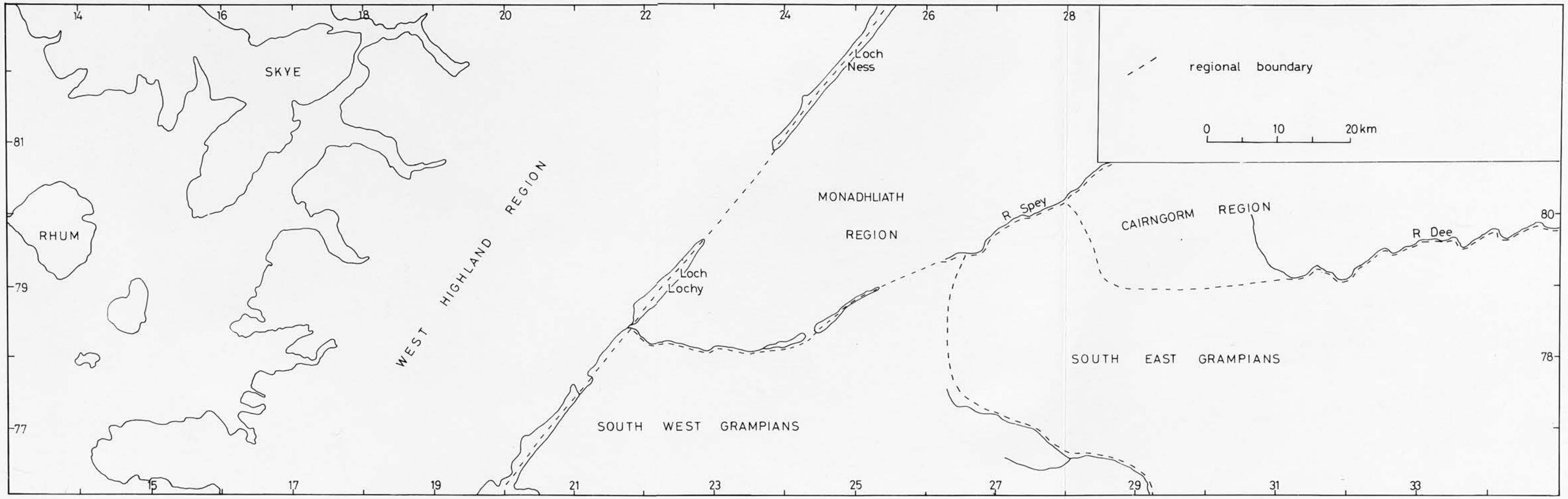


Fig. 2.3 Regional Division of the Study Area

the mountain area is being discussed in the text it appears with an initial capital letter (e.g. Cairngorm Region). Since climatic elements tend to vary along a continuum across space it was necessary to begin by dividing the area in a climatically arbitrary manner. Thus, for example rock wall distributions and attributes in the W Highlands were compared with those in the Cairngorms. Analysis was also carried out at an intermediate scale when several regions were considered together.

Method of Analysis

Analysis of the data was carried out using simple mapping and graphing techniques and by statistical methods. The statistics employed varied from simple descriptors to inferential use of analysis of variance and multiple regression. Quantitative analysis was aided by the use of a computer, using an interactive system, the Edinburgh Multi-Access System (EMAS) with an IBM 475 machine where possible. Elsewhere IBM 370 and ICL 2980 computers were used. The Statistical Package for Social Sciences (SPSS) was employed for certain statistical test as outlined by Nie et al. (1975). In some instances the conditions for use of a parametric test were not fulfilled and the equivalent non-parametric tests were substituted as suggested by Siegel (1956) with the help of a hand calculator. Trend surface analyses of the data were carried out using the Trend Surface Analysis program contained in the SYMAP computer package (Harvard Graduate School of Design, 1976).

Orientation data were analysed using rose diagrams and orientation diagrams (Andrews, 1965; Goldthwait, 1970). Vector analysis (Curray, 1956; Evans, 1977) and the A_n directional statistic (Dale and Ballantyne, 1980) are also considered in Chapter 7. Simple mapping and graphing of distributions were used in preference to more elaborate statistical techniques where they were adequate.

Conclusions

Previous attempts to define cirques objectively on morphological grounds for morphometric analysis have been unsuccessful. Cirques are composed of a steep rock wall head and an apron, the latter of which cannot be defined consistently. The rock walls of cirques can be delimited readily from large scale maps and aerial photographs for features ranging from well-defined forms to poorly developed valley heads; rock walls also occur where no cirque is present. This study is concerned with the distribution and variation of all rock walls. Thus no definition of a cirque is offered, but a simple criterion has been objectively applied throughout the field area. Rock walls that may or may not be parts of cirques have been identified. Once a rock wall had been identified and located a set of descriptors was drawn from the topographic and geological maps. These descriptors are used in the subsequent analysis in an attempt to understand the evolution of rock walls.

CHAPTER 3

THE FORMATION AND DISTRIBUTION OF FORMER GLACIER SOURCE WALLS

Introduction

This chapter is devoted to the study of the spatial distribution of rock walls in the field area. Following consideration of the processes involved in their erosion, the distribution of rock walls is mapped and density values calculated for each region. The resulting patterns are discussed in terms of the factors required for net glacial accumulation over ablation. Regions that appear anomalous are discussed in greater detail.

Formation of Glacier Source Walls

An essential preliminary to understanding the general distribution pattern of former glacier source walls in the field area, is to consider the processes that produced them. Since only cirque-forming processes have been considered in the literature it is these that will be discussed here.

The main processes thought generally responsible for the formation of glacial cirques are abrasion, joint-block removal and frost-riving (Embleton and King, 1975, p.229). Abrasion occurs along the floor and sides of the cirque where the bedrock is mechanically ground down by contact with debris in the moving glacier sole which is itself abraded (Flint, 1957, p.100). In a study of the flow characteristics on Vesl-Skautbreen, McCall (1960) found that the rock surface beneath the glacier remained unfrozen throughout the year so that frost-riving at the bedrock surface did not occur. He also suggested that abrasion was more active than plucking at the time of the study because of the presence of rock flour on the surface of the rock bed and the similarity in direction of glacier movement and striae on exposed parts of the bed.

Joint-block removal is not a question simply of ice plucking rock from the solid bedrock surface exposed to it since ice at $0^{o}C$ possesses a small yield stress in shear in comparison to rocks. Thus the value for glacier ice is $1kg.cm^{-2}$ whereas in gabbro, for example, it is about $160kg.cm^{-2}$ (McCall, 1960). Also, in temperate glaciers the rock surface is separated generally from the ice by a film of meltwater. It seems likely that joint-block removal is capable of little more than removing material already loosened by riving. The other possible aid to plucking is removal of rock already loosened by dilation jointing. Battey (1960) considered that headwall erosion by cirque glaciers incised in gneisses was largely controlled by dilation joints roughly parallel to the cliff face. There, joints arise spontaneously in a direction normal to the cirque headwall as the stresses in that sense are relieved by erosion. Thus the existence of the cirque headwall leads to further growth of the feature provided that the blocks are subsequently removed by the glacier (Linton, 1963).

The third mechanism appropriate to the excavation of glacial cirques is freeze-thaw action or frost-riving. Johnson (1904) found evidence for a large concentration of freezing and thawing at the base of the bergschrund that he descended in the north facing glacier on Mount Lyall, Sierra Nevada. The bergschrund was about 45m deep and in the lowest 10m, rock replaced ice on its northern side. Thus an air passage was open to the subglacial rock floor. Meltwater was present and he concluded that there probably were diurnal temperature fluctuations across freezing point causing a zone of vigorous frost-riving and rock disintegration.

The bergschrund theory has been largely discredited for several reasons. Firstly, bergschrunds are not apparent in all cirque glaciers, and when present do not reach the solid rock surface when the headwalls are very large (Embleton and King, 1975, p.233). Secondly, the air temperature must cross freezing point frequently for riving to occur and this has not been found to be so in temperate glaciers. McCabe (1939) was one of the first workers to measure temperatures within a bergschrund and he found, in August, in Spitzbergen that the temperature even within 10m of the glacier surface remained close to $0^{o}C$.

Battle (1960) recorded summer temperatures at Tverrabreen in Norway and at the Jungfraujoch, Switzerland, and carried out laboratory experiments on the disintegration of rock at various temperatures below freezing. He found that the rate of temperature change within bergschrunds was very slow, varying from $0.2^{o}C$ to $0.02^{o}C$ per hour when a change of at least $1^{o}C$ was occurring outside the bergschrund. Secondly, the temperature range within the bergschrund was very slight, varying between $0^{o}C$ and $-2^{o}C$ in summer. Thirdly, there were no marked diurnal changes across the freezing point during summer. His laboratory experiments showed that little disintegration occurred when rocks were exposed to these small temperature cycles across $0^{o}C$. He concluded that freeze-thaw action can only be important where the rocks are exposed to freely circulating air close to the glacier surface.

A theoretical study of the efficacy of the various agents of erosion was carried out by Boulton (1974), using the Vesl-Skautbreen cirque as a model. Here a maximum slip velocity of $2.33m.yr^{-1}$ and greatest ice thickness of 75m were both recorded by McCall (1960) at the equilibrium line. Boulton's calculations showed that with this order of velocity plucking and crushing (which together, he termed quarrying) would only be effective on extremely weak rocks and would require ice some 100m thick. He suggested that blocks sapped from the headwall of the cirque would enter the glacier sole to be utilised as abrasive agents, although he offered no mechanism, other than falling through the bergschrund, for their arrival at the base so rapidly.

Conditions for the Erosion of Cirques

Each of the processes of cirque excavation (abrasion, joint-block removal and frost-riving) requires certain conditions in which to work satisfactorily. The erosion of the basin or curved shape of the headwall slope and floor area, as represented in a semi-circular long profile in the Cairngorms by Sugden (1969), or more realistically by a family of exponential functions of the form

$$y=k(1-x)e^{-x} ,$$

by Haynes (1968), is largely explained by the abrasion of the lower wall and floor by the moving ice. Clark and Lewis (1951) considered that there was an inherent tendency to rotate in some small glaciers where maximum accumulation occurs towards the headwall and maximum ablation towards the snout, shading from insolation by the surrounding topography being least here (Embleton and King, 1975). Boulton (1974) inferred that maximum abrasion occurs at the equilibrium line of a cirque glacier where thickness and velocity rise to their maxima.

Battle, in showing that freeze-thaw action is not applicable over much of the glacier-bedrock interface, did conclude that it does occur where the rock wall of the cirque is exposed immediately above the accumulation zone of the glacier. If the rock walls are engulfed by ice they cannot retreat due to sapping. If Boulton is correct in supposing that the main tools for the abrasion of the floor by the glacier sole are derived directly from blocks sapped off the exposed headwalls, this process is also diminished.

Excavation of the ground surface to form features of a cirque-like or glacier source wall appearance is thus likely to take place only under specific glacial conditions. Although they may be occupied by cold glaciers, formation or enlargement of cirques under cold ice is unlikely (Andrews, 1975, p.117). For example, Selby and Wilson (1971) found glaciers occupying cirques in the McMurdo Oasis with an englacial temperature of $-20^{0}C$, which, they concluded were not eroding their beds at present, since no rock flour was observed in the meltwaters issuing from the glacier snouts. It also appears unlikely that cirque formation would continue after an area has been swamped by the accumulation of ice to altitudes above the rock walls of each source area. Frost-riving would not occur and abrasion would not take place selectively at the base of the ice. Thus, during inundation by major ice-sheets, the floor and the back wall regions would not be preferentially eroded but the cirque form may be partly or wholly destroyed. However, enlargement does take place when the cirques are occupied by discrete bodies of ice (during the build-up of ice-sheets and during partial glaciation) through selective erosion of the floor and rock walls by abrasion, joint-block removal and frost-riving.

Distribution of Cirques in Scotland

Linton (1959) studied the distribution of cirques over the whole of Scotland in an analysis of the morphological contrasts between western and eastern Scotland. He found that the vast majority of the 473 landforms that he considered to be cirques lie towards the west coast. 179 of Linton's cirques occur within the present field area and are indicated in Fig. 3.1. This shows that the distribution across the area is not uniform but that there are distinct clusters. Linton pointed out that the pattern is not only related to the occurrence of high ground, for he pointed out the similarity between the distribution of cirques and areas with high precipitation at the present day. He considered that the present day precipitation pattern does not vary greatly from that which prevailed during partial glaciation, and that therefore, precipitation decreased greatly away from the oceanic moisture source.

Robinson _et al_. (1971) identified 175 well-defined cirque floors in Scotland of which about 50 occur in the present field area. No explanation of the distribution was offered and several clear features were omitted.

Sale (1970) located 1117 cirques in Great Britain of which about 300 occur in the field area. He based his interpretation on Linton's ideas.

Distribution of former Glacier Source Walls

The source walls of former glaciers were located by the author and their distribution mapped as presented in Fig. 3.2. 458 rock walls, believed to have been headwalls of glacier accumulation areas at various times, have been found on the mainland, Skye and Rhum. The number of rock walls is significantly larger than the number of glacial cirques identified by Linton. The discrepancy results largely from differences in definition between the two forms. In some cases walls exist where lateral development to true cirques has not taken place; in other cases the rock wall area can be clearly identified although the complete cirque is poorly developed. The relationship between cirques and source walls is fully

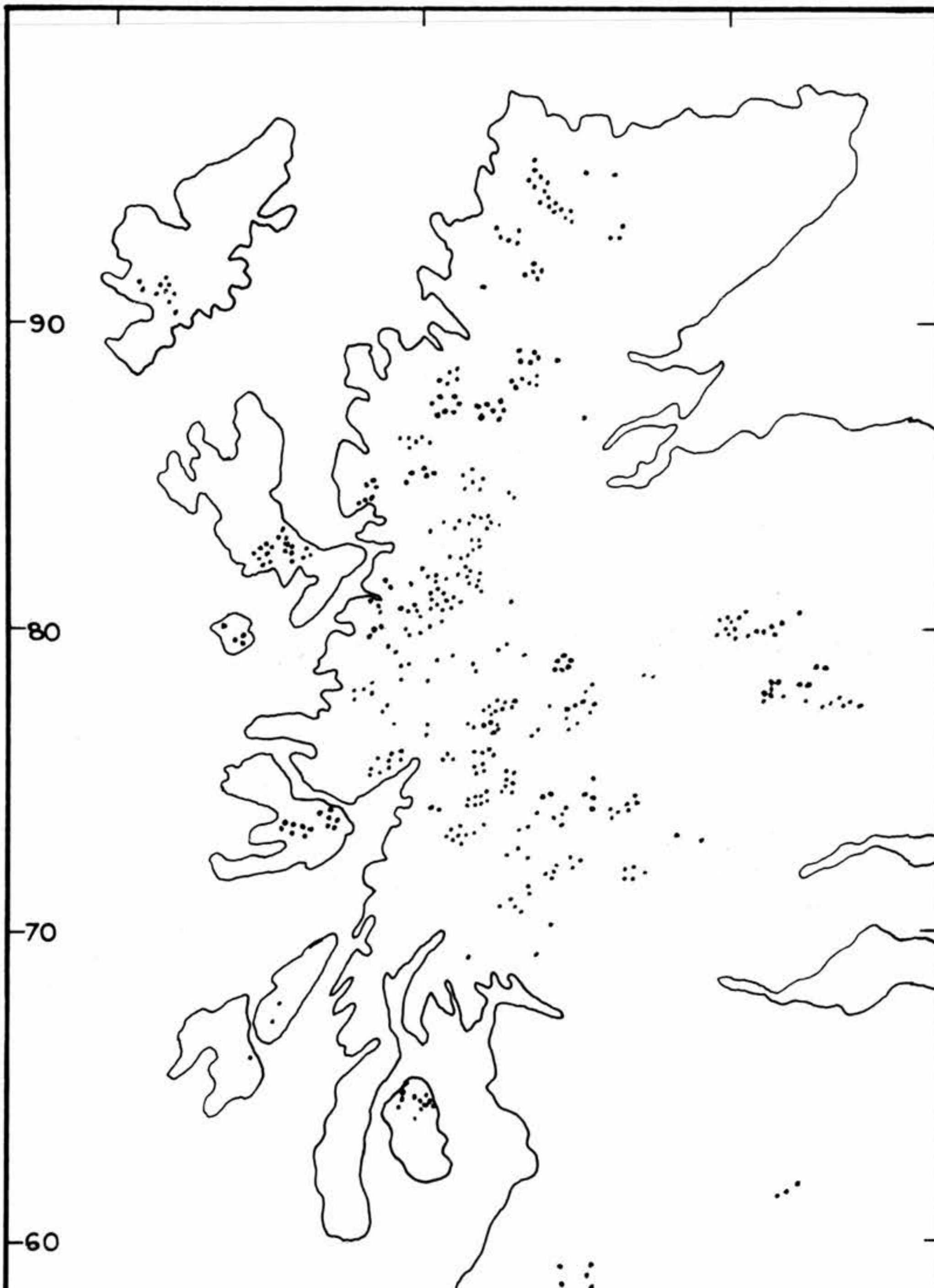


Fig. 3.1 Distribution of Cirques in Scotland, after Linton (1959)

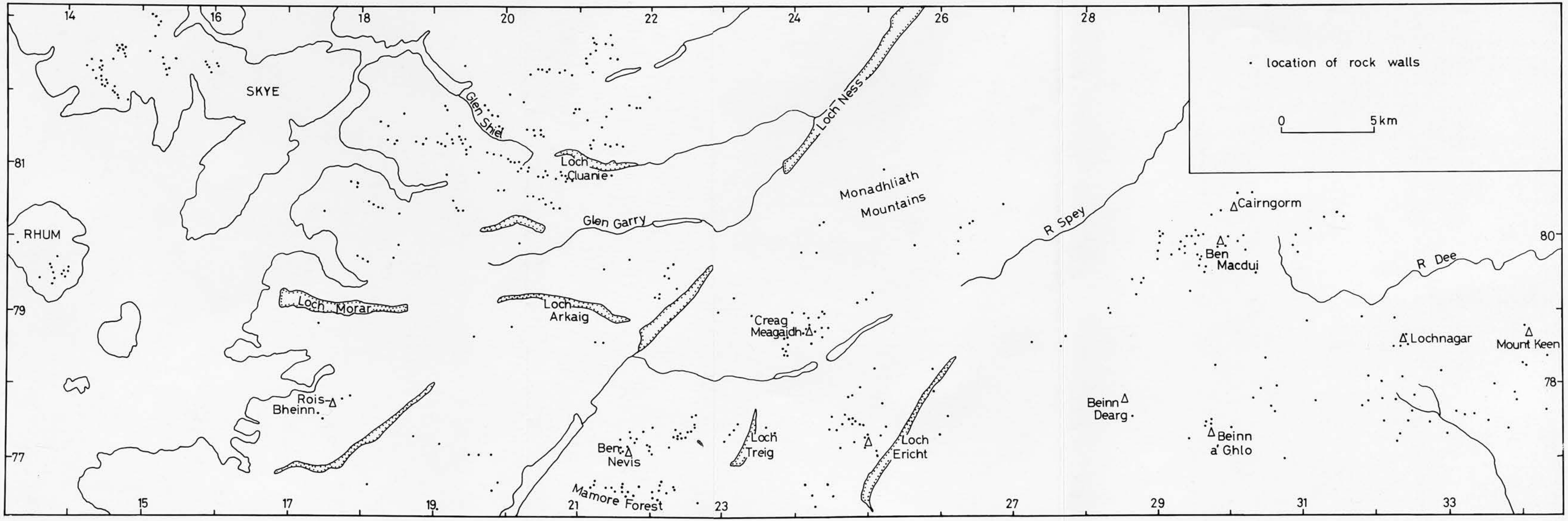


Fig. 3.2 Distribution of Rock Walls

discussed in Chapter 9; this chapter deals only with differences in their distribution patterns.

Fig. 3.2 shows that glacier source walls are not evenly distributed over the field area: instead there are clusters of rock walls in some places and large highland areas devoid of them. Rock walls are more common in the west than in the east. The islands of Skye and Rhum both contain large clusters (Fig. 3.3), while on the mainland the greatest concentration of rock walls occurs west of the Great Glen towards the northwestern edge of the field area (Fig. 3.4). Numbers drop sharply south of the east-west trough of Glen Garry; and also eastward of the eastern ends of Loch Loyne and Loch Cluanie. Within the area to the NW of this are 133 former glacier source walls.

South of Glen Garry is an area almost lacking in glacier source walls. A small number is present around Rois Bheinn, north of Loch Shiel, but elsewhere rock walls occur sparsely and singly. Eastward from Loch Loyne and Loch Cluanie few rock walls were found. Here the land falls to low altitudes aound the Great Glen but rises again to the Monadhliath Mountains, a large tract of high ground in which rock walls rarely occur (Fig. 3.5). Eastwards, across the Spey valley is a high plateau forming the Cairngorm Region of the field area (Fig. 3.6), in which 47 rock walls were found. Within this region the rock walls are almost all located around the summits of the Cairngorm Mountains, with few occupying the plateaux to the north and east.

The SE Grampians (as shown in Fig. 3.7) have a distribution pattern of rock walls quite different from elsewhere. Here, the glacier source walls do not cluster about the summits but tend to occur singly and are widely spaced around the edges of the rolling plateau. They are, however, most common towards the SW-NE trending Highland Boundary Edge and diminish in number away from this. An exception is the cluster of rock walls on

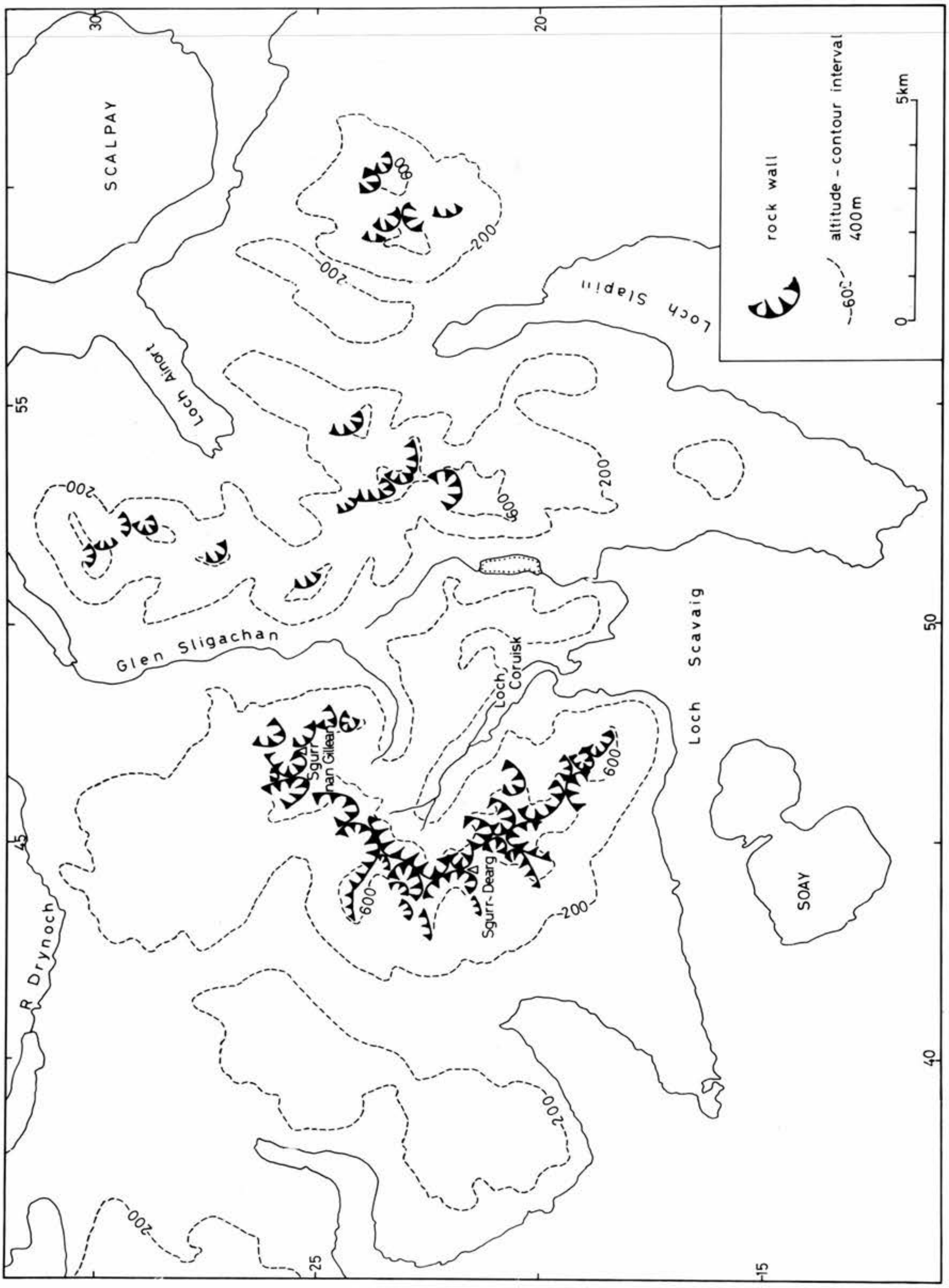


Fig. 3.3a Rock Walls on Skye

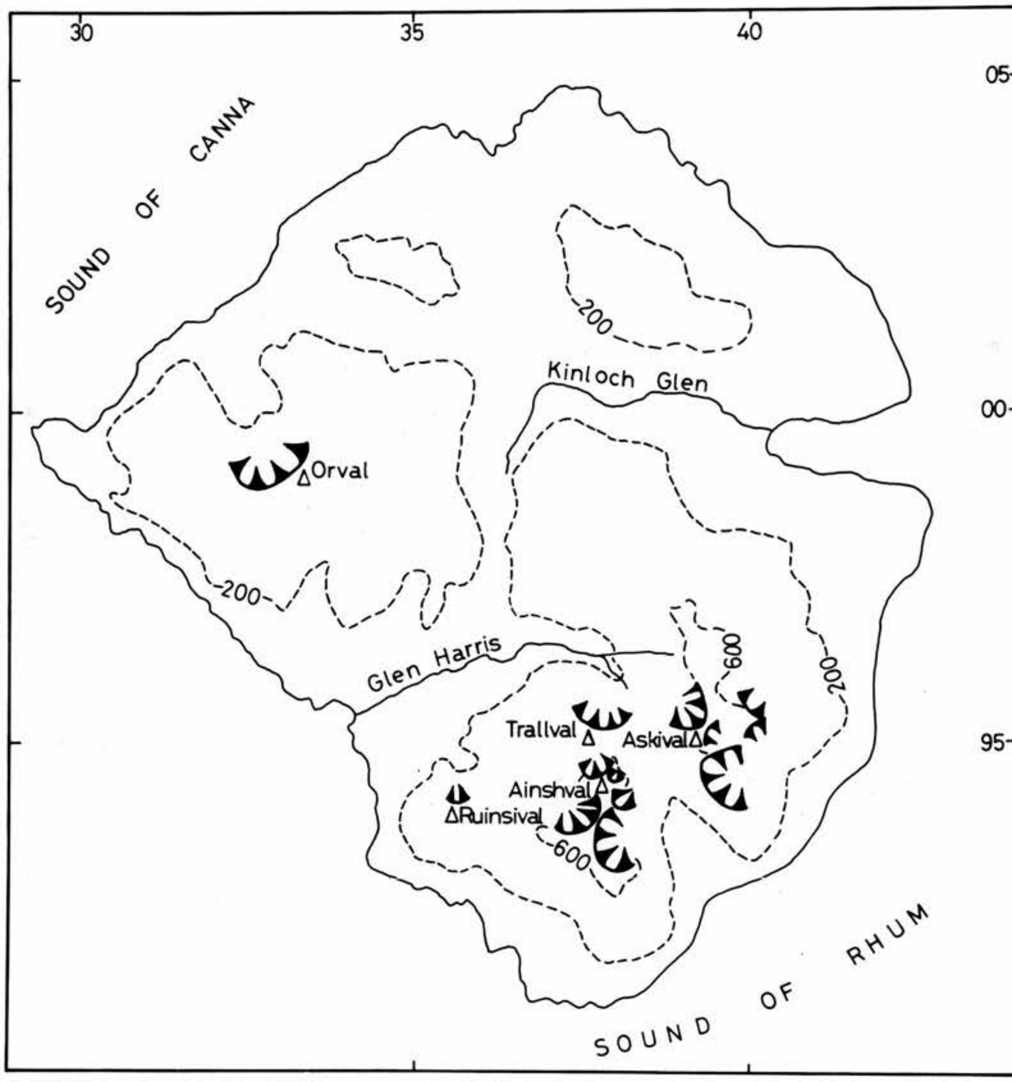


Fig. 3.3b Rock Walls on Rhum

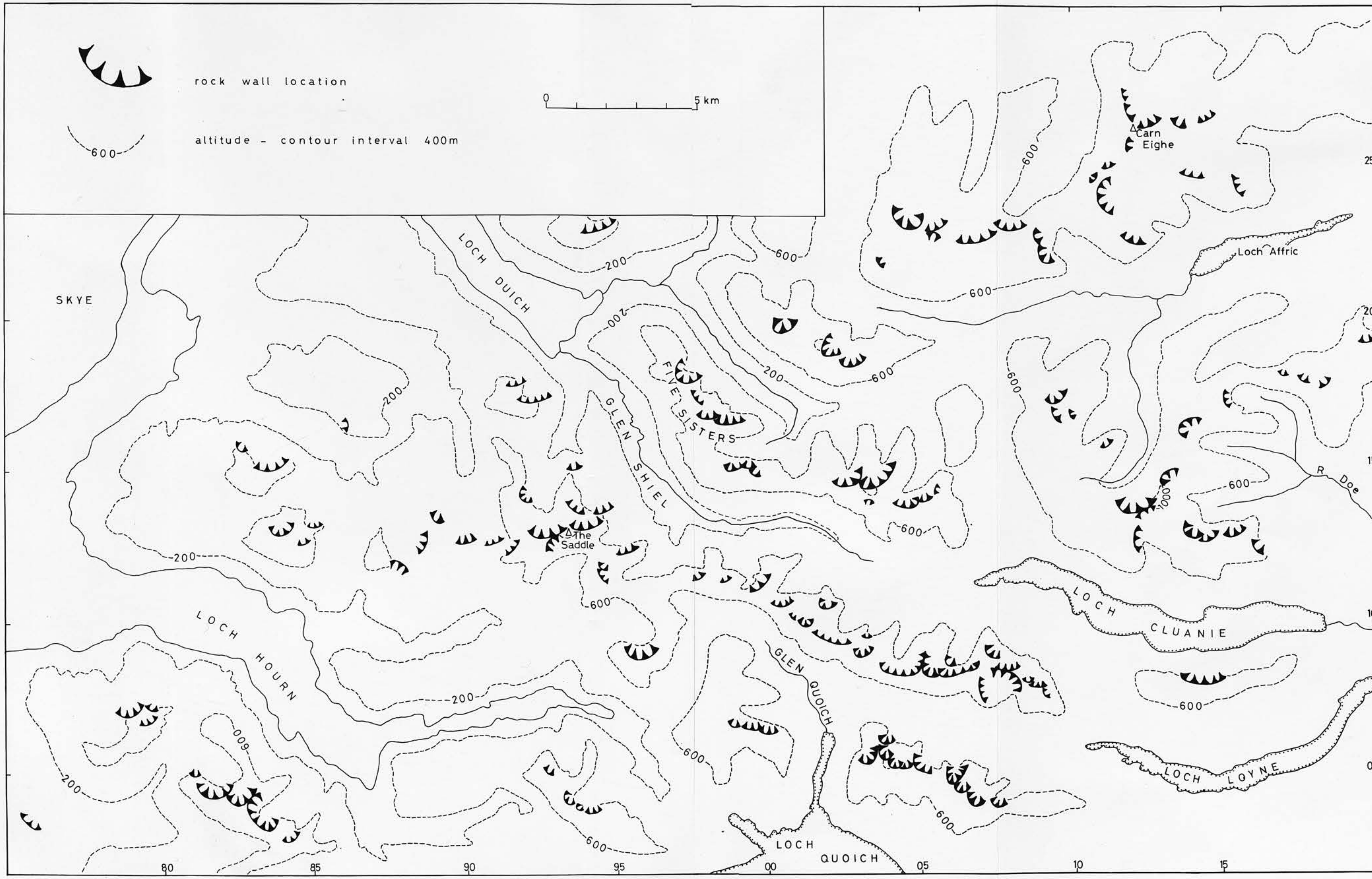


Fig. 3.4a Rock Walls in the northern West Highland Region

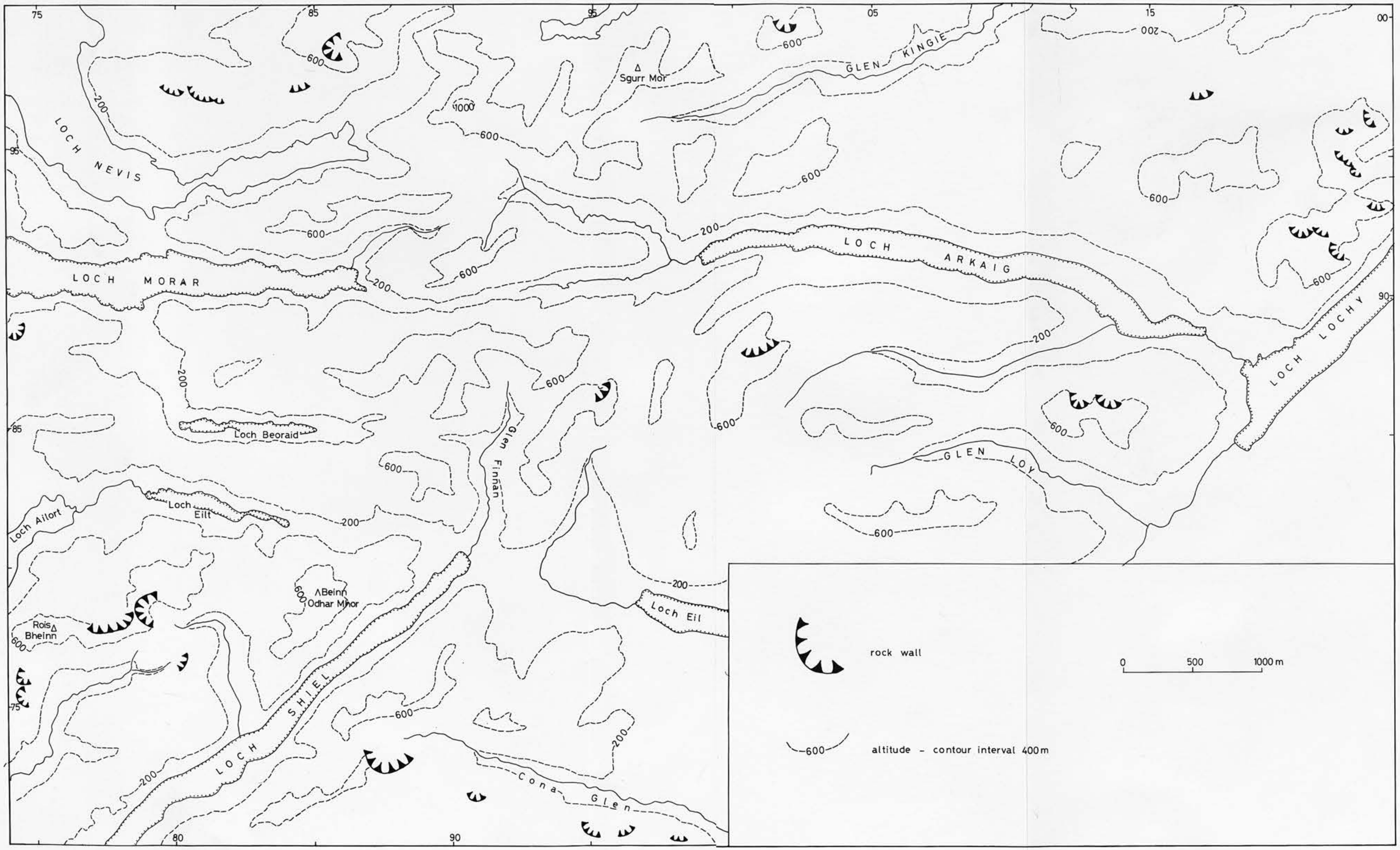


Fig. 3.4b Rock Walls in the southern West highland Region

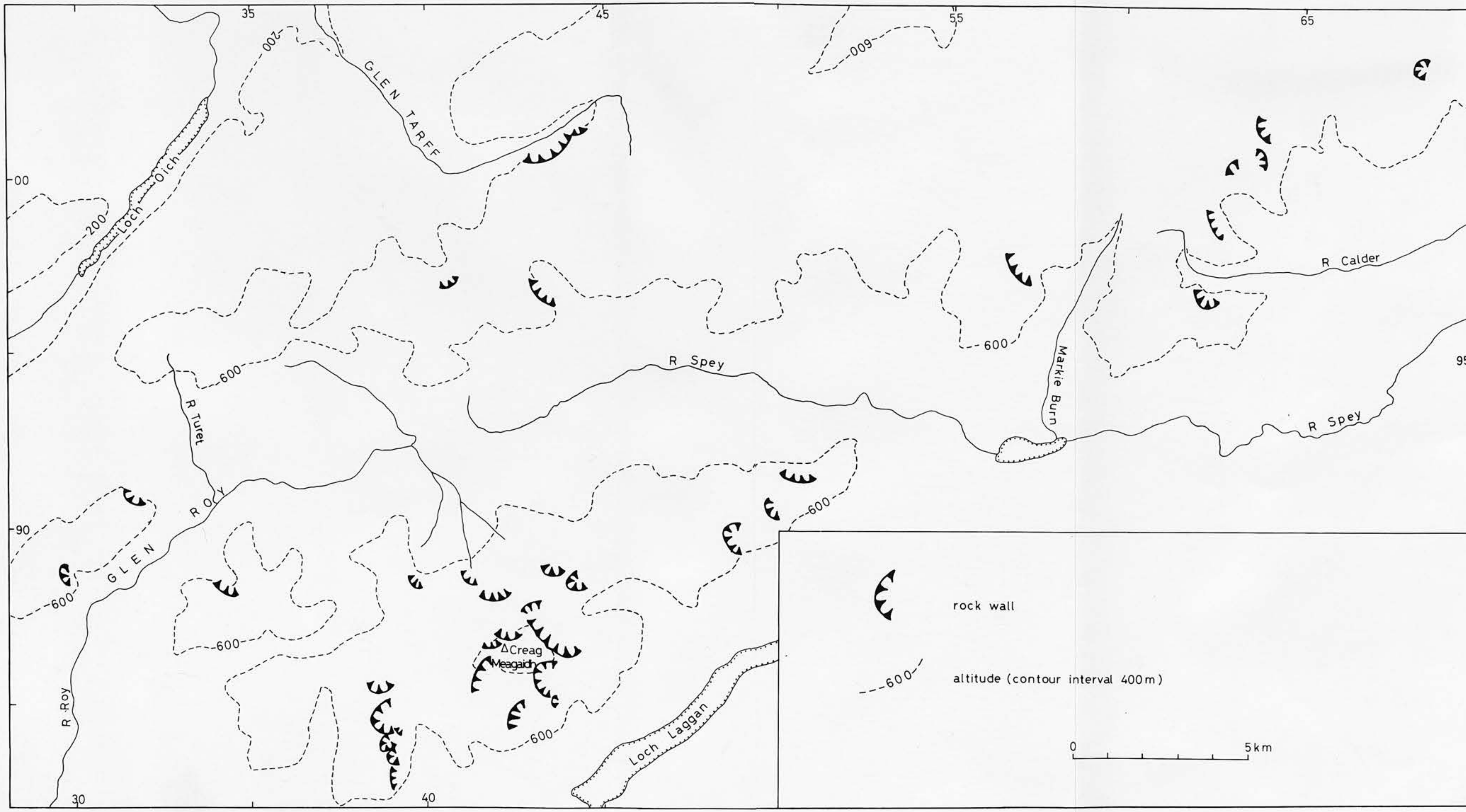


Fig. 3.5 Rock Walls in the Monadhliath Region

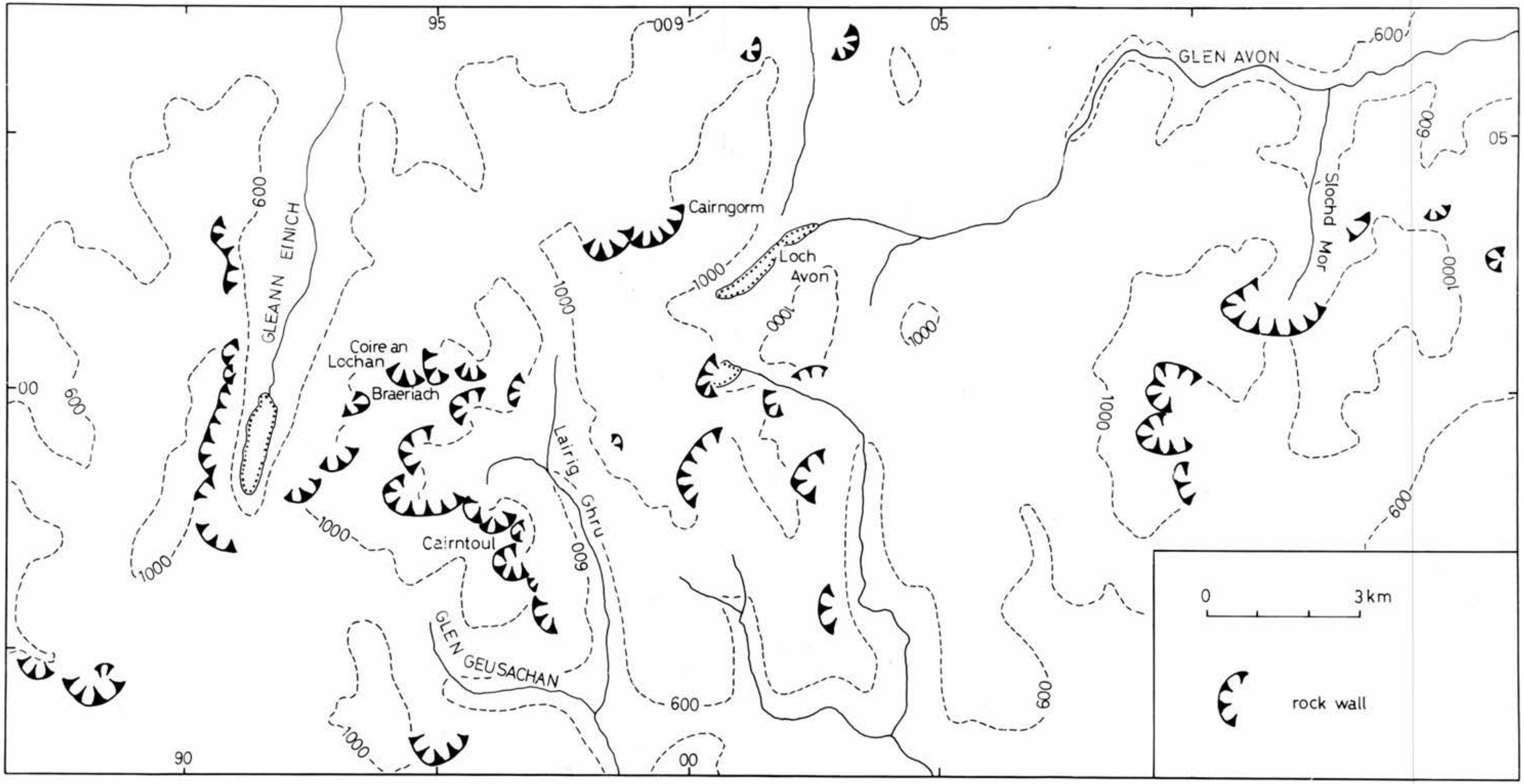


Fig. 3.6 Rock Walls in the Cairngorm Region

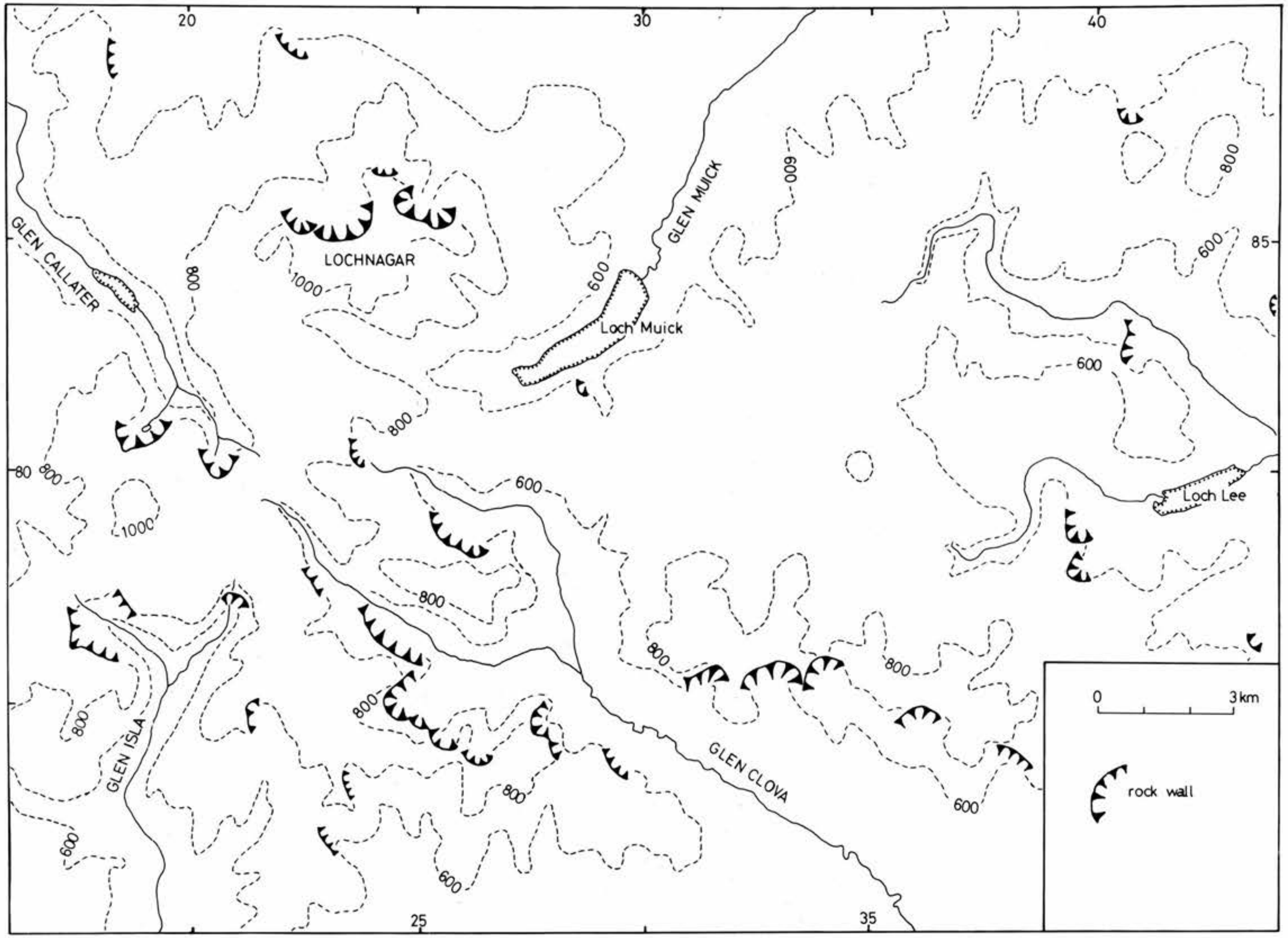


Fig. 3.7 Rock Walls in the SE Grampian Region

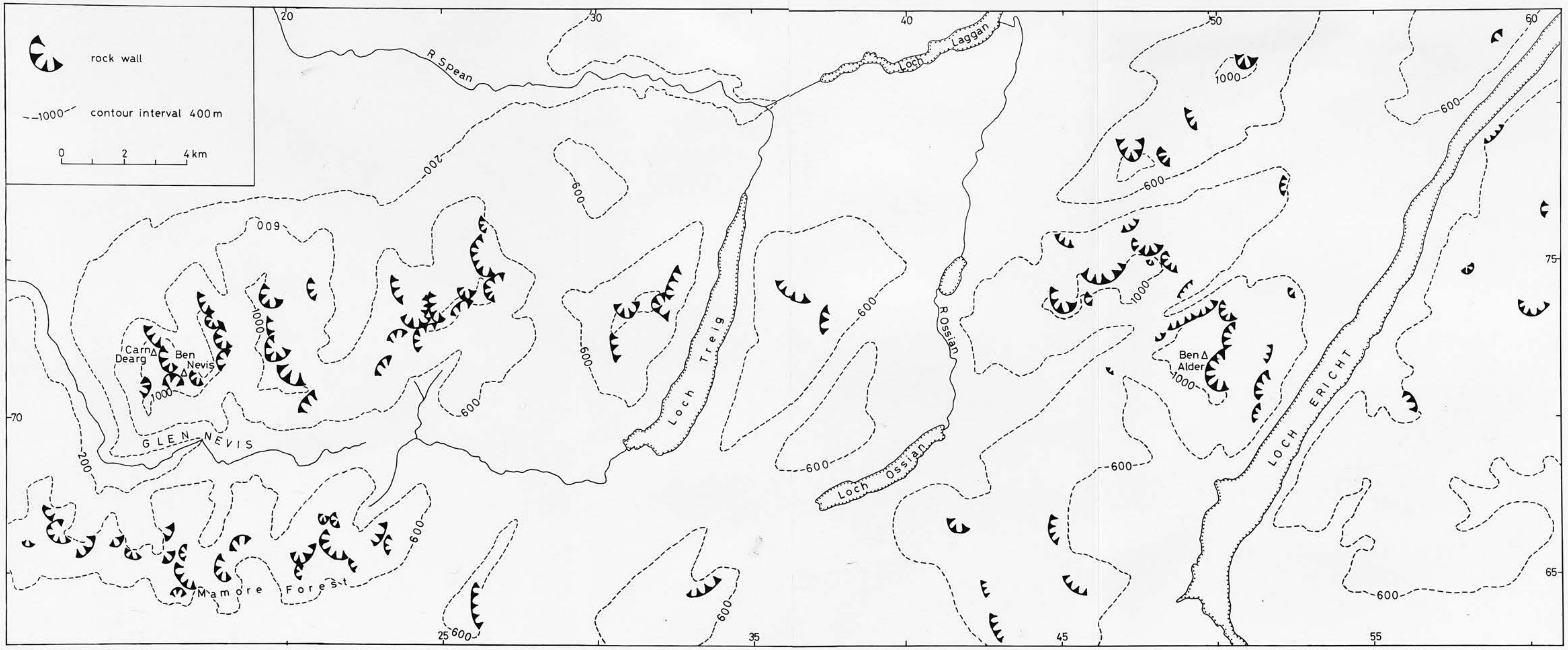


Fig. 3.8 Rock Walls in the SW Grampian Region

the northern side of Lochnagar, the highest mountain in the SE Grampian area (1155m). Westward from the Highland Edge rock wall occurrences decrease until clusters appear around the Ben Alder plateau. Farther west large numbers of rock walls are located in the Ben Nevis and Mamore Forest area (Fig. 3.8), and also north of Glen Spean around Creag Meagaidh.

The overall distribution of former glacier source walls thus presents a complex pattern across the field area, composed of distinct clusters and gaps. Only in the SE Grampians is a more uniform distribution approached.

Density patterns of Glacier Source Walls

Andrews and Dugdale (1971) in attempting to explain the factors controlling glacierization of cirques in Okoa Bay, Baffin Island, outlined 17 characteristics related to the glaciological condition of each cirque. A density index was chosen to represent the spatial distribution and degree of spatial organisation inherent in the pattern of cirques. One of the findings of this study was that spatial density is closely related to the degree of glacierization experienced. Since glacier source walls in the field area are strongly clustered it might be expected that a study of density would help to explain their distribution.

The concept of density in geographical analysis is straightforward, but is, in fact, surrounded by large problems of ambiguity, since it is difficult to quantify in a meaningful and unbiassed manner. Density in this context is simply a measure of the number of occurrences of rock walls in a given spatial unit. The inherent problem is that of the definition of areal boundaries that is common to all spatial analysis (Openshaw, 1977). Openshaw presented a technique for overcoming this problem when the data are initially aggregated into small spatial units. Since the data here are not of this nature his solution by inverting the data is not attempted. Sawicki (1973) summarised the problem of statistical inference when spatial data are aggregated, to obtain (for example) density values, and contended that the unit of spatial analysis employed determines to some extent the results obtained.

In the context of the present research the problem may be stated simply. Density is closely related to the greatest constraint placed on the location of rock walls, that of the topography of the land surface, which itself has spatial characteristics. Thus the density of rock walls is likely to vary considerably depending on the configuration of high and low land in each spatial unit, and this in turn partly depends on the choice of areal boundaries.

There are several possible approaches to obtaining a density pattern of rock walls across the field area. One method is simply to count the number of rock walls within a given radius, say, 1km, of each wall. This only produces meaningful results for the comparison of locations containing many or few features, since a value of zero will be obtained for locations in which rock walls are found singly at intervals of say, 1.1km, and also for large tracts of land where glacier source walls are absent. Evans (1974, p.144) suggested two descriptors of this type for analysis of cirques, the first to count the number of cirques within 100m and the second within 1km, the choice of radius depending on the topographic configuration. Evans considered that either of these descriptive parameters characterises the density distribution and yields useful information. However, this approach may characterise the distribution of the individual cirque with its neighbours but does not characterise the distribution of cirques within a region for comparison with other regions. A variant of this approach was used by Andrews and Dugdale (1971) when they calculated nearest neighbour densities by connecting each cirque to its nearest neighbour, so forming a series of clusters. Their density index was computed as the ratio of the straight line distance between each pair of nearest neighbours and the number of cirques in the cluster. Both of these techniques assume that the size of cirques and by analogy, glacier source walls, does not vary across the study area and that only one mountain mass is being considered. Since in the present study the former was unlikely and the latter not the case, this approach was not employed.

A second method of defining the spatial organisation of glacier source walls requires that not only the size of the spatial unit but also the position of the spatial boundaries be provided. This involves simply placing a uniform grid over the mapped distribution and counting the number of source walls present in each grid area. This method allows evaluation of the spatial organisation over the whole field area but the choice of grid size is critical, as is the location of grid boundaries, to the final outcome. Too large a grid size means that variation within each unit might be greater than between them; too small a grid size means that the usefulness in summarising the spatial patterns is decreased. The Ordnance Survey 10km grid squares were employed as an entirely objective grid of an appropriate size. Sale (1970) in a study of glacial cirques of Great Britain used the grid method, employing a grid area of $100km^2$. He obtained a density distribution displaying a maximum density in the Ben Nevis area and decreasing in all directions from there.

The density pattern obtained for glacier source walls is given in Fig. 3.9. The map emphasises the areas discussed above where there are many or few rock walls. The greatest concentration of source walls on the mainland is in the West Highlands at the latitude of northern Skye. The SW Grampians,

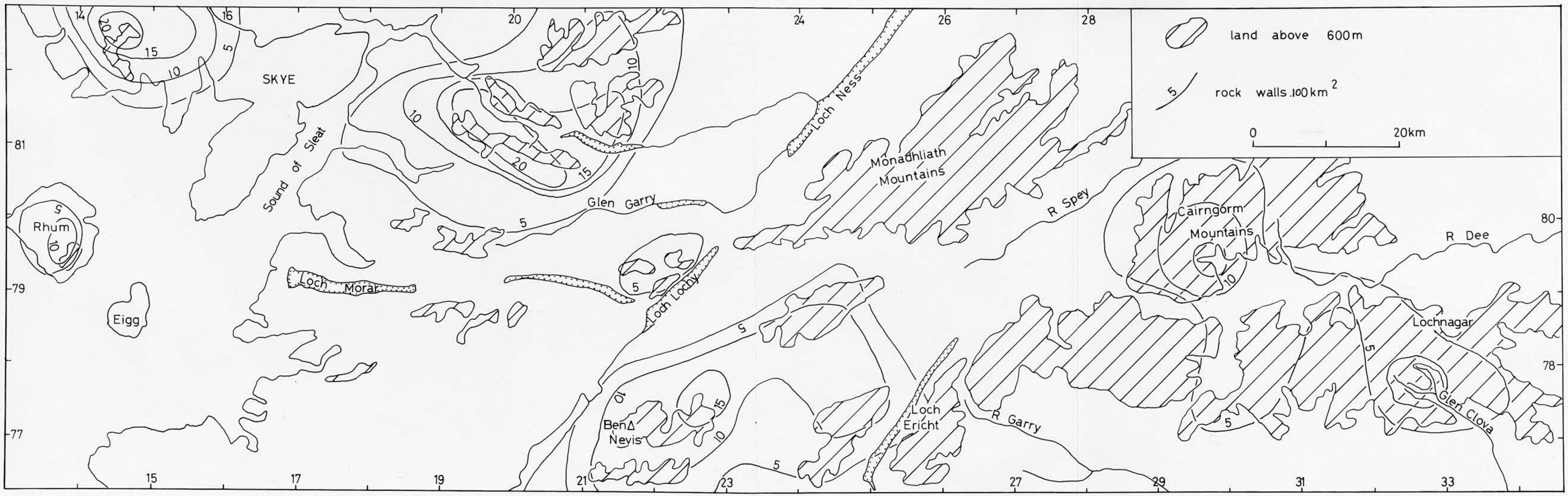


Fig. 3.9 Density Pattern of Rock Walls

southern Cairngorms and SE Grampians also show high densities but elsewhere densities of less than 5 glacier source walls per $100km^2$ are indicated.

The influence of the proportion of high and low altitude land in each spatial unit is indicated by the 600m contour in Fig. 3.9. For example, the square whose SW corner is bounded by 170800 has no land above 600m and one-third of its area in the sea, and has 4 source walls located in it. Nearby, at the square bounded to the SW by 190810 a density of 25 source walls is found. This is largely the result of its topographic make-up of no sea area and much high land, illustrating the large constraint of topography on the location of glacier source walls and their spatial organisation.

A third method of approaching the density configuration of glacier source walls across the field area was undertaken in order to discover the density pattern if altitude is already accounted for. Ceteris paribus there is a minimum altitude in any locality at which glaciers may accumulate (Derbyshire and Evans, 1976). By considering the spatial distribution of glacier source walls above this altitude the influence of height per se is reduced. Several previous workers have suggested how the minimum altitude of rock walls varies. Trenhaile (1975) found that part of the variation of cirque altitude can be explained statistically by the altitude of the mountain summits into which they are incised: the higher the summit altitude the higher is the tendency of the base of the glacial cirque. Secondly, Linton (1959) constructed height-distance diagrams of the altitude of cirque floors and their distance from the west coast, in Scotland, to give four east-west belts based on the National Grid. He found that although there is a wide height range at any easting there is a general rise in cirque altitude from west to east. These results suggest that the minimum altitude capable of supporting glacial cirques and glacial source walls varies across the country in a regular fashion and is also likely to vary between mountain groups.

The field area was divided into seven topographic regions. These are the same as the six described in Chapter 2, except that the West Highland region was divided into two units along the axis of the Glen Garry trough. The minimum altitude capable of supporting glacier source walls was assumed to equal the lowest mean rock wall base altitude in each of these areas. The area above this altitude for each topographic region was found graphically and density values were also calculated. Table 3.1 indicates the results of this analysis. Using this method the SW Grampians has the highest density of rock walls in the field area, suggesting that here the greatest use was made of available sites. This area, in the Andrews and Dugdale terminology, displays the greatest degree of glacierization.

Table 3.1 Density Pattern of Rock Walls

Region	Area(km^2)	N	Density(km^{-2})	Min. Altitude (m)
Cairngorms	340	47	0.138	650
Monadhliath Mts	610	40	0.066	540
SE Grampians (1)	810	34	0.042	400
SW Grampians	440	93	0.211	550
Skye and Rhum	173	59	0.341	280
W Highlands (2)	760	133	0.175	300
W Highlands (3)	820	28	0.034	270

Notes:
(1) East of Glen Shee
(2) North of Glen Garry
(3) South of Glen Garry

The SE Grampians has a density figure lower than that which might be expected from the density map produced in Fig. 3.9. This may have resulted from the extremely low altitude of the base of the lowest rock wall in this area. North Carlochy rock wall (NO408831) has a mean base altitude of less than 360m, some 40m lower than any others in this area. Sissons and Sutherland (1976) calculated a very low altitude for the equilibrium firn line of the last glacier that accumulated against the North Carlochy rock wall and suggested that accumulation was largely the result of snow having been blown off the large plateau surface to the SW of the rock wall. From his work on cirque locations in the Urals, Dolguishin (1961) suggested that glaciers could accumulate in such circumstances far below the climatic minimum altitude for the area. It is likely therefore that the minimum rock wall altitude in the SE Grampians is not climatically determined but is largely related to the plateau topography.

A further property of regional cirque floor and firn line altitudes which is commonly displayed complicates this approach to density. The altitude tends to rise systematically across any region rather than maintaining a steady average elevation. Thus it is anticipated that the minimum altitude for cirque erosion varies across each region of the study area. The altitudinal variation is discussed in detail in Chapter 6. An attempt is made in the following sections to determine reasons for the variation in spatial organisation of glacier source walls as shown in Figs 3.2 to 3.9.

Comparison of Cirque and Glacier Source Wall Density Patterns

Sale (1970) is the only previous worker to have produced a density distribution pattern of cirques in the field area. He found that density decreases in all directions from the Ben

Nevis area. He agreed largely with Linton (1959) who found that only 8% of cirques in Scotland lie in the eastern half of the country.

The density distribution of source walls is different from that of cirques. Using the same technique as Sale, the maximum density is in the Western Highlands, although taking altitude into account it is in the SW Grampians. Even though the number of cirques as presented by Linton is comparatively low in the area bounded by Glen Garry (roughly, Northing 800), Loch Sunart and the Great Glen, there is not such a marked diminution as in the distribution of glacier source walls. 24 out of a total of 179 glacial cirques in the present field area are located in this region. The writer found 28 of a total of 458 rock walls in the same area. In relative terms these represent 13% and 6% of the total numbers of glacial cirques and glacier source areas respectively. Table 3.2 shows the proportional variation for all the topographic units and these are all seen to vary much less than in the southern West Highlands. It is suggested that the disparity in the latter area is due to different interpretations of the same landforms. In this area several cirque-shaped features were noted and, although they had walls composed of rock the walls themselves were gently sloping (under 20^{o} (see Chapter 2)).

Table 3.2 Distribution of Glacial Cirques and Former Glacier Source Walls

Location	Cirques(1)	Source Walls	%Difference
NW Highlands	56 (31.3%)	133 (29.0%)	+2.3
SW Highlands	24 (13.4)	28 (6.1)	+7.3
Skye and Rhum	23 (12.8)	59 (12.9)	-0.1
SW Grampians	30 (16.8)	93 (20.3)	-3.5
SE Grampians	18 (8.9)	58 (12.7)	-3.8
Cairngorms	17 (9.5)	47 (10.3)	-0.8
Monadhliath	11 (6.1)	40 (8.7)	-2.6

Notes (1) as published by Linton (1959)

Factors limiting the distribution of Glacier Source Walls

The factors that limit the formation of glacier source walls are largely identical with those that limit the distribution of glaciers (except that some glaciers were not nourished beneath rock walls). Three main factors are apparent as limiting the distribution of glacial accumulation areas: climate, topography and spatial relationships with other ice masses. These variables are all inter-dependent in terms of their effects on the distribution of source walls.

Whether an area is glaciated or not primarily relates to the regional climate. The actual glacier distribution is dependent on the balance between accumulation and ablation at locations within the glaciated region. Accumulation of snow results from precipitation directly onto the surface, redistribution of snow from higher ground to lower by drifting in the wind, and avalanching from unstable snow-covered slopes to those of gentler gradients. Ablation results from solar energy incident at the surface, convection of heat from the atmosphere and condensation of water vapour (Paterson, 1969, p.56). Derbyshire and Evans (1976) demonstrated that the distribution of glaciers accords with some simple rules. First, glaciers occur at higher latitudes because of lower radiation input. Secondly, they occur at higher altitudes because of lower temperatures and increased precipitation. Thirdly, more maritime location are favoured because of increased snowfall and cloudier summer conditions. Fourthly, slopes facing poleward are preferred because they receive least solar radiation and eastward facing slopes because ablation is more effective in the afternoon with higher air temperatures. Fifthly, leeward aspects are favoured because wind-drifted snow can accumulate there, and these slopes being sheltered reduce the amount of ablation due to decreased turbulent mixing of the lower atmosphere. Finally, topographic concavities encourage glacial accumulation because of advantages in exposure and shelter.

The first factor considered by Derbyshire and Evans above concerns variations in solar declination with latitude. Since the latitudinal extent of the study area is only 70km this factor was discounted as an influence on the distribution of rock walls.

The final three factors mentioned above, poleward and eastward, leeward and in topographic concavities, apply at the local scale. Thus, they may affect the distribution in all glaciated regions but their relative and absolute importance vary. Closeness to the moisture source for snow-bearing winds is a regional effect and altitude is important both regionally and locally. In considering the general distribution of glacier source areas it is these two factors that require analysis.

Altitude has several effects on the budget of a glacier since precipitation increases with altitude while temperature decreases. This not only has the effect of decreasing the length of the ablation season and increasing the amount of precipitation received directly from the atmosphere, but it also increases the proportion of precipitation that falls as snow.

The relationship between glacier source walls and altitude is roughly shown in Fig. 3.10. This indicates that 70% of the rock walls have their base altitude above 600m, so that they are mainly a high altitude phenomenon. However, from the location of rock walls relative to the 600m contour in Fig. 3.9, and from Linton (1959), it is evident that the altitude of rock walls varies across the country, and that other factors are involved. Chapter 6 studies the regional altitude pattern of rock walls. Attention is drawn here to the localities where the altitudinal relationship is not displayed. Thus, in the Monadhliath Region

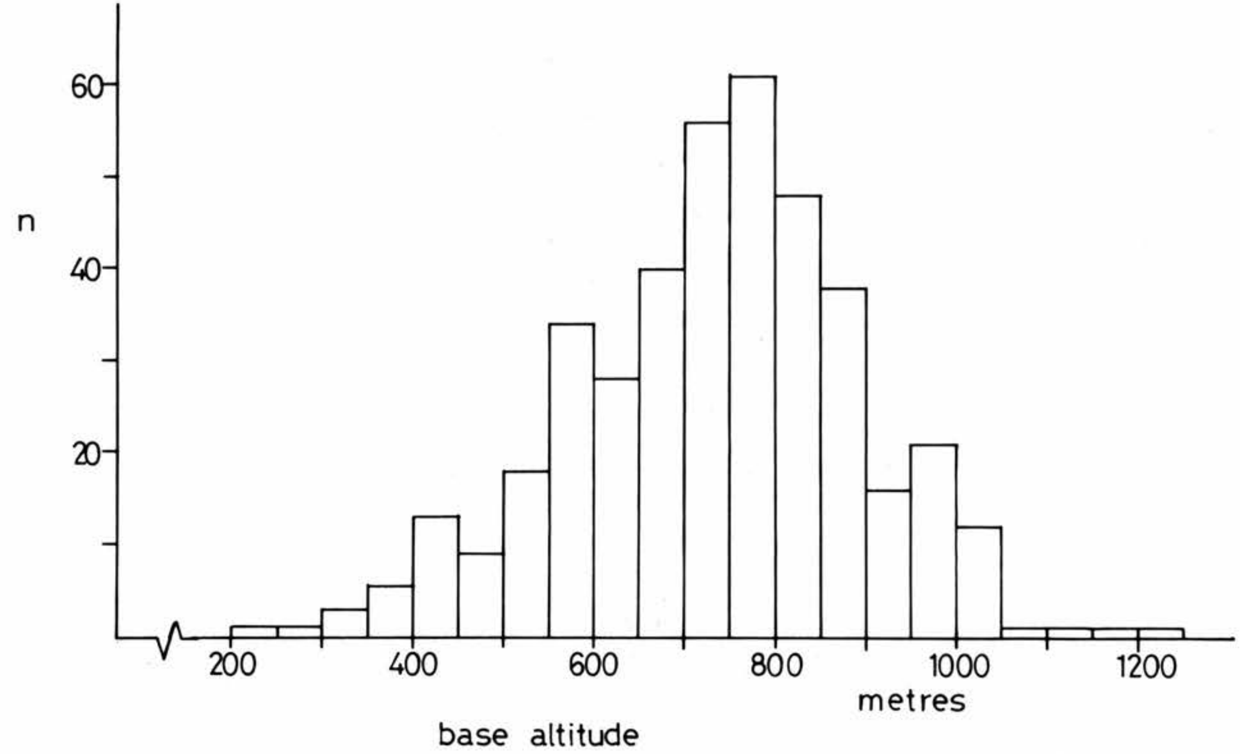


Fig. 3.10 Range in Rock Wall Base Altitudes

of the field area, the Monadhliath Mts themselves are an area of many rounded summits with much land at altitudes that elsewhere have supported rock wall development. The vast majority of rock walls in this Region occur farther south around the significantly higher summits of Creag Meagaidh and Beinn a' Chaoruinn. In the southern part of the West Highland Region summit altitudes are much higher than many rock wall base elevations immediately to the north.

Although temperature varies with latitude as well as with altitude, the variations in incident solar radiation over the latitudinal range of the field area are not significant. It is assumed throughout this study that as well as latitudinal solar declination temperature variations are negligible.

Precipitation, however, does vary considerably across the study area. Inferences concerning the distribution of former glacier source areas based on the distribution of present-day precipitation are based on the assumption that the direction of the precipitation gradient was the same when rock walls were being formed, although absolute and relative amounts may have differed greatly. Linton (1959) interpreted the higher density of glacial cirques in western Scotland as a response to the climatic gradients developed during glacial times. He showed that the majority of cirques occur in areas where the present precipitation is more than 2000mm, and that the rest are located in areas currently receiving more than 1500mm mean annual precipitation. He inferred that the cirques developed in response to a precipitation distribution comparable to that of present day. A close association between the present-day precipitation distribution and the last occupation of cirques in the Lake District was also suggested by Manley (1959).

The assumption that the distribution of precipitation during glacial times was similar to that at present must be questioned, consideration being given to the relative importance of each available moisture source, now, during partial glaciations and during ice sheet conditions. Lamb (1972b, p.264) classified present weather types over Great Britain by considering the prevalent atmospheric circulation associated with each. Of the seven types (see Chapter 1) persistent precipitation accompanies only airstreams enjoying a sufficient sea passage in which to absorb a considerable amount of moisture. These airstreams are generally westerlies carrying depressions from the Atlantic, but occasional northerly and easterly airstreams bring precipitation to eastern areas, having travelled over the Norwegian Sea and North Sea respectively.

During partial glaciation and at the outset of ice sheet build-up the North Sea would have been an insignificant moisture source for easterly airstreams for several reasons. First, with a lowering of the eustatic sea level, the North Sea would have had a much smaller surface area from which moisture could have been absorbed. Secondly, with lower temperatures the sea surface might have been frozen over for much of the year, thus precluding moisture absorption by the atmosphere. Thirdly, when the North Sea was not frozen, it was certainly cooler than at present and so the capacity of the atmosphere to absorb moisture from it was less. This is because moisture available to an air mass passing over a water surface is substantially reduced with a decrease in surface temperature (and, consequently, air temperature), since there is an exponential decay relationship between decreasing temperature and the vapour pressure that can be exerted (McIntosh and Thom, 1969, p.18).

With the increasing accumulation of ice leading to full ice-sheet conditions such as at the Late-Devensian maximum, the role of the North Sea diminished further, until, if the British and Scandinavian ice masses were ever confluent in the North Sea, there was no moisture source present. In that situation the northern North Sea was ice bound and the southern North Sea was above the sea level of the time.

A decrease in significance as moisture sources is envisaged for the North Atlantic and the Norwegian Sea. Lamb and Woodroofe (1970) suggested that for most of the last 70,000 years the North Atlantic and Arctic Oceans were ice-covered. Ruddiman and McIntyre (1976) analysed cores from the bed of the NE Atlantic and found that during conditions of full glaciation, ice-bearing polar water completely occupied the North Atlantic above latitude 45^{o}N. Thus, during the accumulation of ice sheets the southward-migrating oceanic polar front inhibited the usefulness of the North Atlantic and Norwegian Sea as moisture sources; they may even have been largely frozen over for much of the winter. From an oceanic core located at 52^{o} 35'N, 21^{o} 56'W Ruddiman et al. (1977) showed that even during the Loch Lomond Stadial the oceanic polar waters had advanced as far south, in the eastern Atlantic, as southern Ireland.

From the evidence above and considering that accumulation of snow is particularly a winter occurrence, it is apparent that, as the climate deteriorated either to a partial glaciation (such as the Loch Lomond Advance) or at the outset of full glaciation moisture sources available to airstreams passing over the British Isles became largely restricted to the warmer middle and tropical Atlantic water masses, situated to the SW. This does not imply that easterly and northerly airstreams did not pass over the field area, but that airstreams arriving from the SW were necessary to accumulate solid precipitation during the build-up to all glacial maxima. With the configuration of topography across Scotland and the direct relationship between precipitation and altitude, the favourability of the southwestern part of the study area would have been accentuated through both orographic and frontal precipitation-producing mechanisms.

Discussion

The geomorphological evidence agrees with the hypothesis that glacial accumulation is closely related to the precipitation gradient across the country, the greatest dissection of the topography having occurred in western Scotland (Linton, 1959). The distribution of rock walls, which essentially represents the distribution of former discrete glacier accumulation areas, concurs to some extent. Fig. 3.11 shows the relationship between glacier source walls and the present-day precipitation pattern.

The rainfall map indicates that mean annual precipitation is generally related not only to altitude but also to distance away from the west coast. Thus, the Cairngorms receive only half the rainfall of the mountains SW of Loch Quoich, even although the Cairngorm plateau is at a higher altitude. Given that during glacierization airstreams approaching from the SW were the principal precipitation-bearing ones, the disparity was much greater than at present. Even so only 10% of the 399 rock walls on the mainland are located outside the present 1600mm isohyet, the majority of these occurring in the SE Grampians. The highest densities of glacier source walls are coincident with areas of hypothesised high precipitation and the highest mountains, but there are some peculiarities.

The Monadhliath Mts and the SE Grampians consist of plateaux of approximately similar altitudes, with summits of about 900m. At present the 1600mm isohyet includes all the high ground of the Monadhliaths but only parts of the SE Grampians. The difference in numbers of rock walls is inconsistent with the evidence of present-day rainfall. In the SW Grampians there are many former source walls that today receive less than 1600mm; in the Monadhliath Region all but one source wall are located well within the 1600mm isohyet. The simplest solution to this

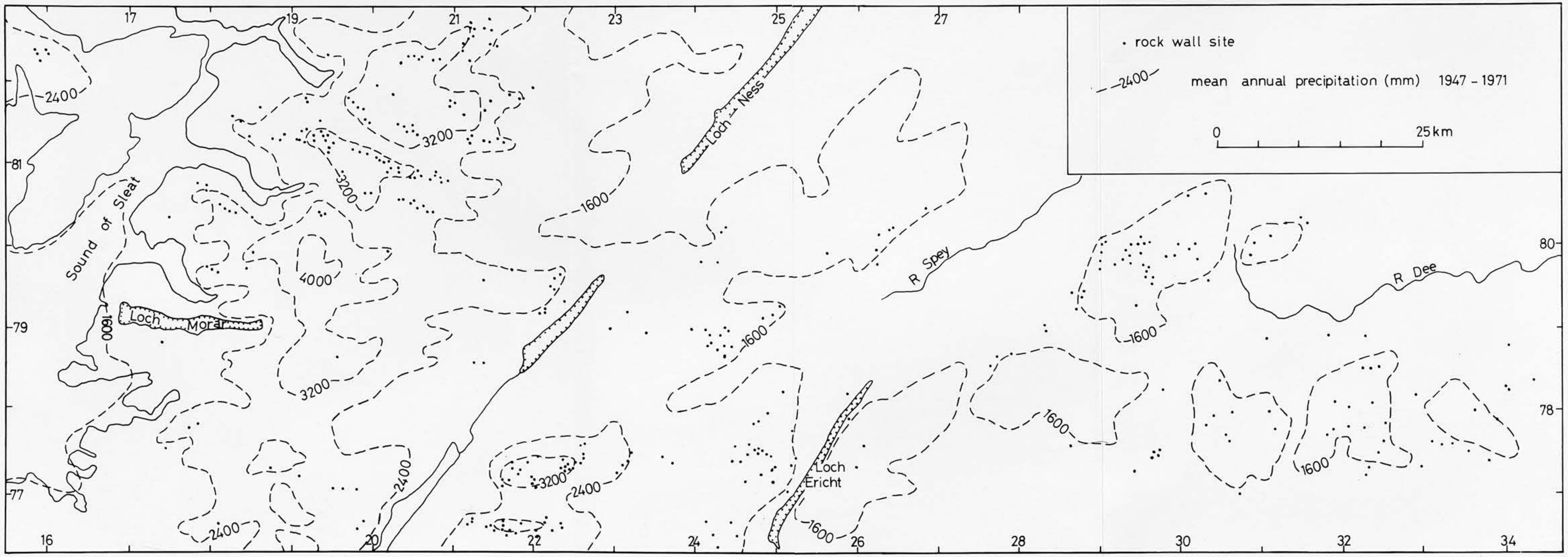


Fig. 3.11 Rock Walls and the Present-day Precipitation Pattern

apparent contradiction is to propose a southerly component to the precipitation gradient, as would be expected from an oceanic polar front located to the SW of Ireland. In that situation the SE Grampians would have received, relative to the present day, more precipitation than the plateau to the north. In an airstream with a southerly component, forced rising across the Highland Edge would have occurred with the effect of encouraging precipitation, while on the northern side, subsiding air would have discouraged it. Also, through the fohn effect the subsiding air would have been relatively warmer (Lamb, 1972b, p.381), thus disadvantaging possible source sites further.

One consequence of this precipitation arrangement is that mean annual precipitation would have varied much more rapidly across the Highlands than it does at present. Evidence from the Loch Lomond Stadial is in some agreement. Pollen analysis carried out by Birks and Mathewes (1978) on cores taken in the Abernethy Forest, Speyside, at 221m on the NW side of the Cairngorm Mts, indicated very high percentages of Artemisia in the pollen assemblage for this time. Most species of Artemisia do not tolerate much snow and hence the abundance of Artemisia implies a rather arid climate with warm summer days but cold winters. Even allowing for an increase in precipitation with altitude these somewhat arid conditions are very different from those that at the same time were causing large glacial accumulations in the south and SW of the study area. Further, a decrease in moisture availability is indicated northwards across the SE Grampians to the Cairngorms from pollen analyses carried out by Walker (1975a, 1975b). Walker found that the stadial percentages of Artemisia present in the pollen assemblages of two sites on the southern side of the SE Grampians were very low. Farther north and west at Loch Etteridge, Glen Truim, the percentage was higher.

A scarcity of precipitation cannot explain the lack of glacier source walls in the southern part of the West Highland Region. The whole region receives more than 1600mm annual precipitation at present; if the above assessment of moisture source availability is correct and the restriction of snow-bearing airstreams to sources south of west increased as the severity of the climate increased, there was always greater precipitation in the southern West Highlands than farther north, when glacier source walls were being formed. The severe glacial scouring and abrasion that characterise this area indicate that, far from being unsuitable for glaciation, this area was favoured to a much greater extent than required to form independent glacier souce walls. Three specific hypotheses related to this theme are presented in an attempt to explain why this area has few rock walls but has been greatly glacierized.

(i) Very rapid glacierization

It is hypothesised here that this area was so favoured for glaciation that the regional glaciation limit was lowered extremely rapidly and accumulation occurred through a wide range of altitudes and in all kinds of site (c.f. Ives et al. (1975). The situation is envisaged where the special advantages of rock wall sites were not required to enhance accumulation and inhibit ablation. Thus specific rock wall sites were not occupied and eroded preferentially during each climatic deterioration. Rather, erosion took place widely across the land surface that was largely submerged under ice. Although absolute accumulation rates are not yet known for any glacierization, rapid glacierization is more likely here than anywhere else in the field area due to the likelihood of high precipitation here compared with elsewhere. Also, since this form of glacierization can only occur where rapid net accumulation takes place, a west coast location in the middle latitudes of the Northern Hemisphere is probably the most favoured situation of all.

Very rapid or 'instantaneous' glacierization occurs under very different conditions to cirque glacierization (as was discussed in Chapter 1) when only the most advantaged sites are occupied by independent glaciers. The two types of build-up could have occurred simultaneously in different areas joined by a steep precipitation gradient. This would have entailed rapid build-up close to the moisture source leading to rapid glacierization while a cirque or partial glacierization occurred in regions with relatively low precipitation. During the Loch Lomond Stadial this spatial variation seems apparent from the morphological and pollen evidence cited above. However, the mechanism does not seem sufficient to cause the sudden decrease in source walls from north to south in the West Highland Region (Fig 3.4). A few favoured sites might also be expected to have developed at times when deterioration of the climate was just sufficient to cause glacierization in this high precipitation area, but they are not apparent.

(ii) Variation in intensity of glacial erosion

The southern West Highland area has been more severely eroded by ice sheets than farther north, suggesting that rock walls that may have formed here early in the Quaternary were subsequently destroyed, the Loch Lomond Stadial not being long enough for them to be re-eroded. With the ice shed of the Late-Devensian ice sheet migrating eastwards through time from the present watershed (Peacock (1970) indicated from the trend lines of ice movement that it was located east of Loch Eil), the 'catchment' areas for the northern and southern parts of the West Highland Region would have differed greatly. South of Loch Arkaig the West Highlands would have received ice-streams moving westwards from the Ben Nevis area and the SW Grampians. However, north of Loch Arkaig a shift eastwards in the ice shed position had less effect since the area north of Glen Spean was in the precipitation shadow of the mountains to the SW and south. Hence not only was accumulation greater in the southern part of the West Highland Region but greater volumes of ice passed through, greater thicknesses and velocities were involved and thus more severe erosion took place.

(iii) Geological variations

A third possible explanation for the scarcity of glacier source walls in the southern West Highland Region may lie in geological variations across the West Highlands. In a study of the effects of ice sheet erosion on valley patterns in Scotland Haynes (1977) found the Glen Shiel - Loch Quoich area was anomalous in terms of the preservation of unbroken mountain barriers and low connectivity between valleys. This is the area of highest rock wall densities. Farther south high valley connectivity values coincide with the area of low rock wall densities. Haynes attributed the variation in connectivity to ice streaming from the Lochaber and Ben Nevis areas across the southern West Highlands, and to geological differences. A band of highly inclined pelitic schists runs from Morvern in the SW to Loch Monar in the NE with flat beds of psammites lying to the east (Brown et al., 1970). Haynes noted the coincidence between the highly inclined schists and the long crestlines of the Glen Shiel area, and the coincidence of the flatter lying psammites and the less continuous ridges to the east. She suggested that the pelitic areas represent the highest pre-glacial altitudes and throughout ice sheet occupation they presented a barrier to ice flowing from an ice-shed located to the east of the area while permitting highland glaciation in the form of occupied cirques.

While it is probable that the pelites did form the highest pre-glacial relief there is not a close correspondence between them and the present-day relief. The pelites occur in a broad band with a SW-NE axis but the heights of the summits also rise northwards through this band as does the density of rock walls.

The reasons proposed for the scarcity of glacier source walls in the southern West Highland Region are based on the variation in glacial erosion between this area and that immediately to the north, on a glacial accumulation pattern that decreased sharply from the SW and on topographic variations. The location of the area is favourable to the processes of very rapid glacierization; thus the need for glacier source areas is obviated. Although it is very likely that this mode of accumulation applied at the outset of some or all glaciations, it does not explain the sharp division between the areas of high and low densities of rock walls. It is envisaged that during glacierization ice built up very rapidly across the mostly psammitic summits of the southern part of the region which received the greatest precipitation. With decreasing accumulation through decreasing precipitation northwards and the presence of higher mountains in the pelitic spine, isolated summits and ridges remained nunataks above the ice for long periods allowing rock wall erosion to occur. In addition with the ice-shed moving eastwards the southern part of the West Highland Region was increasingly affected by large volumes of ice streaming westwards.

Conclusions

1. Rock wall erosion is only likely to occur when the source area is occupied by a glacier with a discrete accumulation area. Once ice completely submerges the rock wall it is not enlarged.

2. The general distribution pattern of glacierization across the field area is dependent on the regional precipitation pattern, which is itself dependent on the availability of moisture sources and the configuration of topography.

3. The distribution pattern of rock walls is thus largely related to the precipitation gradient and to altitude. The highest densities and the greatest numbers of rock walls on the mainland occur in the West Highlands and the SW Grampians and so confirm the theoretical argument that it was air masses from the present-day subtropical Atlantic Ocean that controlled the accumulation of snow and ice through precipitation. Rock walls are relatively less frequent in the Monadhliath and Cairngorm Regions despite high plateau altitudes. (The SE Grampians lies between the extremes).

4. Paradoxically rock walls are also scarce where the severest glacial erosion has occurred, and so their relationship with the precipitation gradient is not unique. In areas of high precipitation where the volume of ice that accumulated (possibly by so called instantaneous glacierization initially) submerged the land surface, the erosion of rock walls did not take place.

5. The distribution is also partly controlled by the degree to which the surface was subjected to other types of glacier ice and glacial erosion. This includes not only ice that accumulated _in situ_ but also ice-streams that encroached from elsewhere. Depending on the severity of this erosion it is possible that rock wall forms eroded and enlarged over long periods during the Quaternary were subsequently destroyed. This may have occurred in the southern West Highland Region.

CHAPTER 4

THE DIMENSIONS OF FORMER GLACIER SOURCE WALLS

Cirque Morphometry

The size and shape of cirques have been studied by many authors (e.g. Andrews and Dugdale, 1971; Gordon, 1977). The objects of these studies have been basically twofold; to examine relationships between the cirque variables in order to relate these variables to the processes of cirque evolution and to consider the factors that most influence variations in cirque morphometry. Manley (1959) was one of the first to suggest that the fairly uniform dimensions of cirques are due to their formative processes. He proposed that the length : height ratio of the Lake District cirques is fairly constant because air currents passing over the cirque headwalls enabled snow to drift here preferentially. Many quantitative studies have followed. Initially these were concerned with the variation of two variables, but latterly studies of the range of variability of many variables simultaneously have been possible using multi-variate techniques.

An example of bivariate analysis is the study by Haynes (1968) of the form of the longitudinal profile of cirques in several areas of Scotland. With the aid of a family of exponential curves she analysed some effects of geology on cirque profile.

In a later study Andrews and Dugdale (1971) considered the geometry and degree of development of cirque form in order to analyse the degree of cirque glacierization in Okoa Bay, Baffin

Island. Using discriminant analysis they found that there tend to be morphometric differences between cirques containing glaciers and those that are empty; the cirques with glaciers are larger and also tend to be narrower than those without.

McLaren and Hills (1973) hypothesised a correlation between the extent of former glaciers and the volume of the cirque or cirques at their heads in the Front and Main Ranges, Alberta. They found that 64.5% of the variation in the maximum extent of ice could be explained by cirque area, its elevation and its easting.

Working in a small area of Scotland Gordon (1975) found, as might be expected, that cirque volume was the best single descriptor of cirque size and that the variations in cirque dimensions resulted from local rather than regional parameters, which he expressed in terms of the maximum altitude related to the cirque, the lip altitude, concavity and the gradient of the headwall.

Graf (1976) studied the internal dimensions of cirques in the Rocky Mountains and found that they are most likely to be glacierized if their width is greater than their length and their walls are steep.

Studies such as those by Andrews and Dugdale (1971) and McLaren and Hills (1973) found that the larger the cirque size the greater the likelihood of glacierization and the bigger the occupying glacier. Thus the greater the size of a cirque the greater the development through erosion and the more favourable is the site for glacial occupation. This result was implicitly assumed by Gordon (1975) who subsequently attempted to explain why cirque size varies.

In this study it is initially assumed that the larger a former glacier source wall is, the more suited it has been to glacial erosion. The object is primarily to discover if rock wall dimensions vary across the field area in any systematic manner and to ascribe any such variation to specific causes. A secondary object is to reconsider the initial assumption used here and implicitly by many authors, in the light of what is discovered.

Several working hypotheses may be formulated with the aid of the current literature, which indicates that three main sets of variables are responsible for the variation in cirque, and by implication rock wall, development. These are climatological, geological, and topographic. Although Peterson (1968) assessed cirque development somewhat oddly from the curvature of the long profile, he managed to relate that development to the prevailing precipitation gradient in SE Australia; a conclusion similiar to that of Andrews and Dugdale (1971) and McLaren and Hills (1973). A simple working hypothesis emerges that glacier source walls are best developed in the areas that are most favourable in terms of the regional palaeoclimate, particularly precipitation. The studies by Haynes (1968, 1977) suggest that rock type and structure influence the development of cirque head walls; a finding substantiated elsewhere (e.g. Vilborg, 1977). Thus a second hypothesis is that the development of rock walls is related to rock type. Thirdly, the topography may effect the development of rock walls such that the largest walls occur on the highest mountains, as Gordon (1975) found.

Since a study of glacier source walls is perforce a study of quasi-two-dimensional variables many of the possible morphometric descriptors of whole cirques (Evans (1974, p.141-5) suggested 47) are not only irrelevant but impossible to calculate. Four variables have been selected and measured for each rock wall in the study area: width, amplitude or depth, total wall area and slope angle. The method of calculation of each of these was described in Chapter 2. In this chapter the effects of regional climate, lithology and elevation are examined in terms of variations in amplitude, width, area and slope angle.

Dimensions of Former Glacier Source Walls

The amplitude of each former source wall is the average difference between the rock wall crest and base altitudes as indicated in Chapter 2. Fig. 4.1, which shows graphically the quantitative distribution of rock wall amplitudes, indicates a highly skewed population with a median value of 135.5m and a range from 62.5m to 472.9m.

Rock wall width is the mean horizontal difference between the crest and base of each rock wall. Rock wall width ranges from 82.0m to 693.2m and is also highly skewed, the median width being 178.0m. Width and amplitude are highly correlated. A Spearman rank correlation coefficient r_s between the two variables yielded a value of 0.9053 (n=458), significant at the 0.001 level. Since these variables are strongly correlated future analysis deals only with amplitude as this is the variable more readily related to rock wall development, by its representation, to some extent, of the depth of erosion.

The slope angle of glacier source walls is fairly constant across the field area. Fig. 4.2 shows a range of values from 24.0^{o} to 53.8^{o}, with a normal distribution and a mean of $37.8^{o} \pm 4.3$. Two-thirds of all slope angles occur between 34 and 40^{o}. On a subjective basis it might have been expected that the gradient of rock walls would have been much higher, but the slope angles derived here comprise both the steep upper headwall and the backwall foot zone (Haynes, 1968) which may be

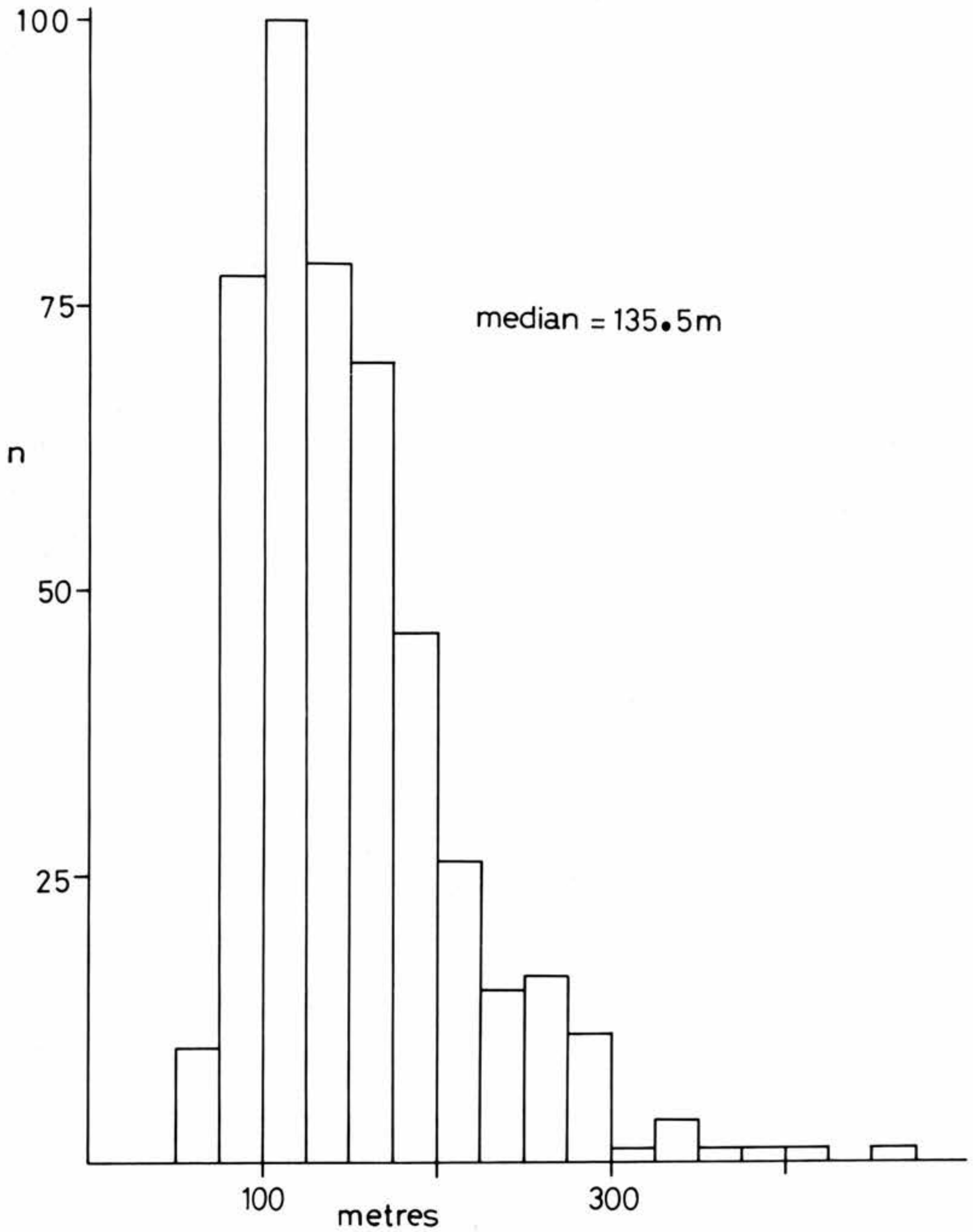


Fig. 4.1 Distribution of Rock Wall Amplitude

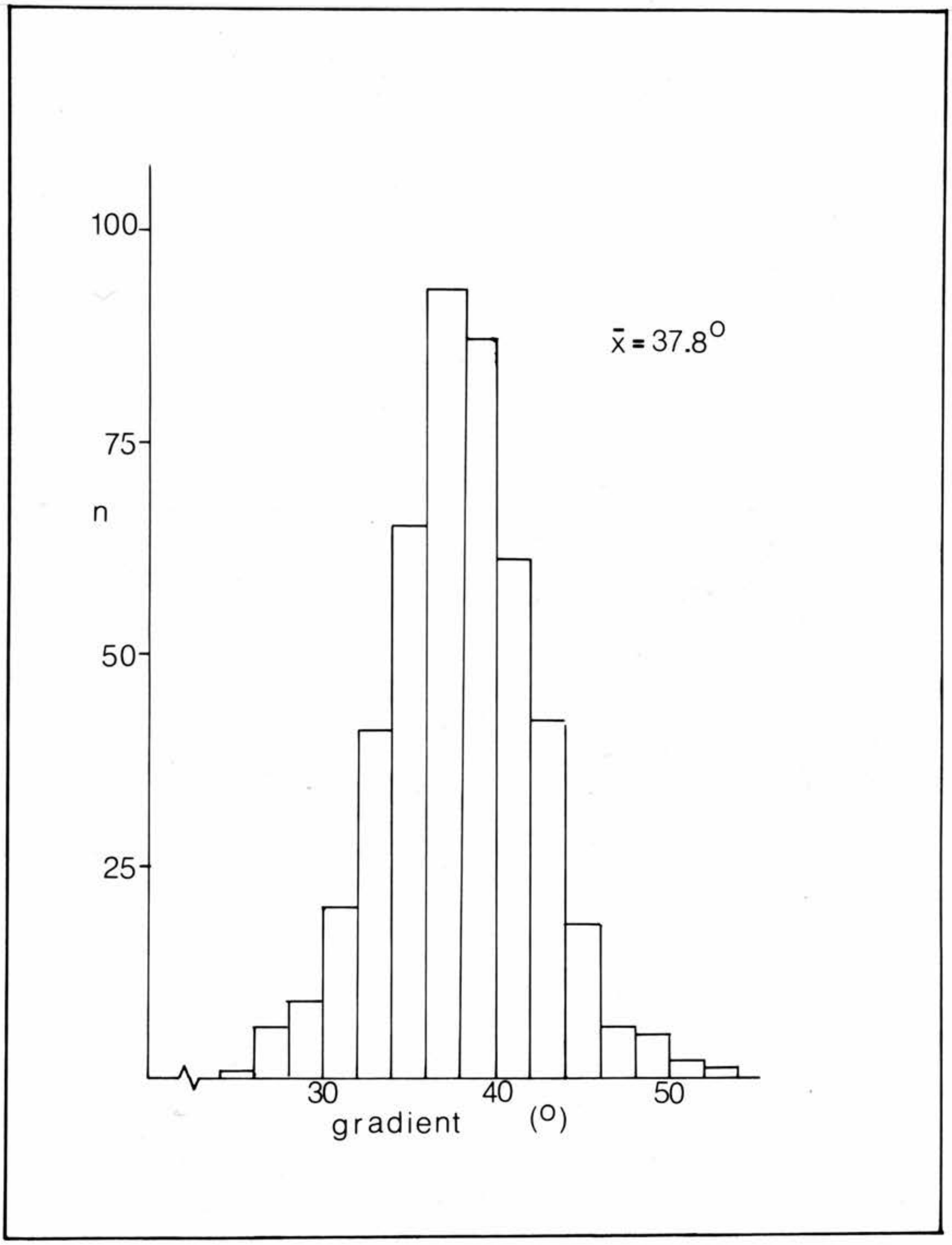


Fig 4.2 Rock Wall Gradient

debris covered and not very steep. In many cases it is possible to walk up glacier source walls, the only difficulties being encountered towards the crest. In order to ascertain if scree cover significantly altered the slope of rock walls, the walls in the SE Grampians were divided into two groups on the basis of presence or absence of debris and a Student t-test was carried out (Blalock, 1972, p.188). At the 0.05 significance level no statistical difference in rock wall slope angle was apparent between rock walls with debris covering part of their slope and those without. In subsequent analysis of slope angle no subdivision was made on this basis.

The area covered by each rock wall was also measured. Area is given as the crest length of the wall times the slope length rather than the amplitude (see Fig. 4.3). Where the rock wall in plane view is significantly curved this calculation over estimates the actual area. A more accurate measure would have been obtained by integrating across the 100m sample transects, where each line and its neighbour, together with the crest and base delimitors, circumscribe a trapezium whose area may be calculated. Since this method would have involved considerable extra mapwork to obtain an improved value for only some glacier source walls it was not undertaken. As with amplitude the distribution of area values is highly skewed, the median value being $0.20km^2$ and the overall distribution ranging from $0.03km^2$ to $2.77km^2$.

Headwall Dimensions of Cirques in Other Areas

Although many authors have studied cirque dimensions, few have published information on the amplitudes of headwalls and their slope angles. Headwall area values have not been published. Gordon (1977) studied 231 features which he defined as simple cirques in the NW Highlands (located on the northern

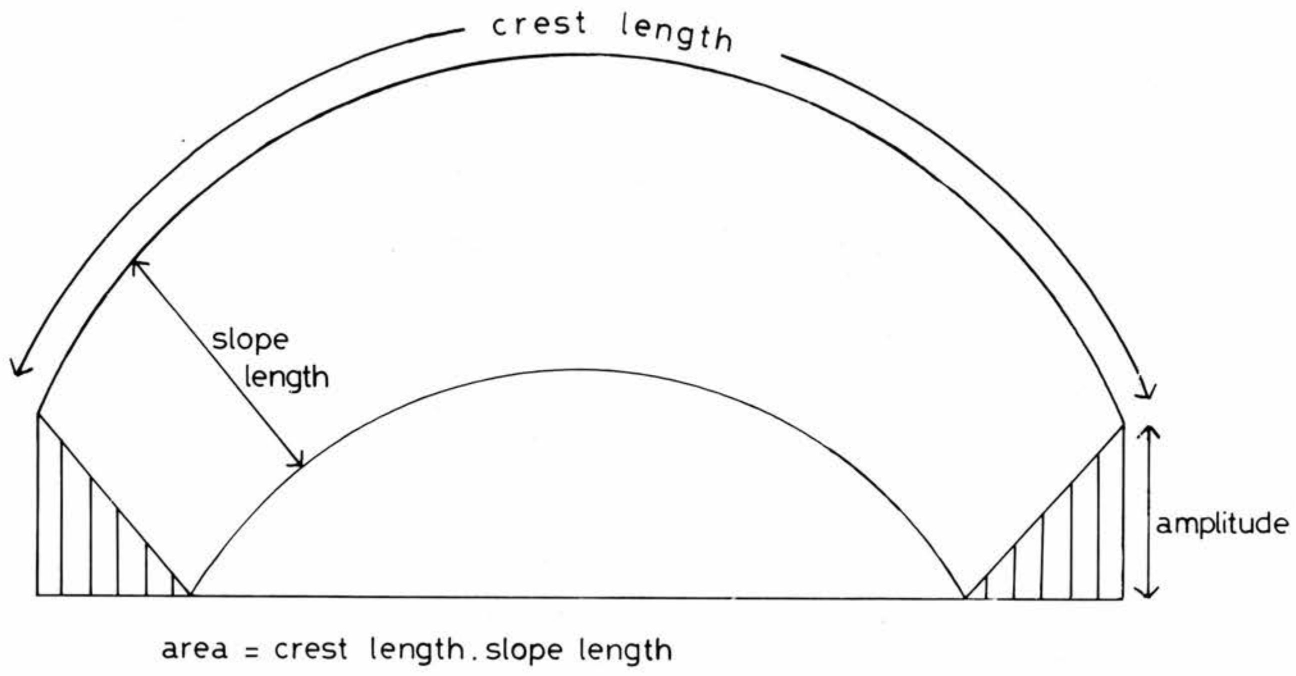


Fig. 4.3 Measurement of Rock Wall Area

margin of the present author's West Highland Region). Measuring amplitude as the difference between the minimum headwall crest and the lip altitude he found a median of 275.6m with a range of values from 92m to 670m. The median and maximum figures are much higher than that for rock walls in the field area and may reflect the variation in definition compounded by the fact that all Gordon's cirques have outward sloping floors and hence represent a maximum amplitude of the cirque. The average maximum headwall angle of these cirques was $44.6^{0} \pm 8.5^{0}$ with a range of 55^{0} from 18^{0} to 73^{0}. This is a much broader range of values than that for rock walls, not surprising at the maximum, but it does indicate some extremely gentle maximum headwall angles.

Graf (1976) calculated the mean cirque amplitude as the mean crest altitude less the floor altitude for eight areas in the Rocky Mountains. He found values from 220m to 600m. He measured slope angle as the arctangent of the ratio of amplitude to cirque length following Manley (1959) and Andrews (1965); this is not comparable with slope angles as measured in the present study, but where the outer limit of the floor is clearly defined it is a most useful ratio.

Andrews and Dugdale (1971) measured the amplitude of the backwall of cirques in the Okoa Bay area and found a median value of 110m. This is quite similar to the median found for the present area and was measured in the same way. They provided no information on the headwall slope angle.

In a study of stone movement within a cirque on Mount Twynam in the Snowy Mts of Australia, Jennings and Costin (1978) found that the headwall of the cirque had an amplitude of 130m and a slope angle of 25^{0}. The amplitude of this cirque is very close to the median for the field area although the gradient of the slope is much less.

Evans (1974, pp.147-8) measured the maximum headwall and minimum floor altitudes of 66 cirques in the Bridge River District of British Columbia. He obtained a mean cirque amplitude of 470m, considerably larger than elsewhere. He also calculated the maximum headwall gradient for each cirque; this has a mean of 64.7^{0} and a range of 31.4^{0} from 46.9^{0} to 78.3^{0}. In order to calculate the maximum headwall gradient Evans averaged gradients over the spacing of one contour interval (30m) but admitted that at this scale large errors result. Quite apart from inherent measurement errors, this parameter is not very useful since it records extreme values and is therefore unrepresentative. It is more likely to be related to the dip and jointing characteristics of the rock (Haynes, 1971) and localised landslips than directly to erosion by an incipient glacier. Evans went on to calculate the profile closure of each cirque by subtracting the minimum floor angle from the maximum headwall angle.

Haynes (1968, 1971) studied the effect of rock structure on cirque shape. She divided the backwall into two parts, a steep upper wall and a more gently sloping foot zone. The modal class for the upper slope was $30\text{-}40^{0}$ with a range from 20^{0} to 90^{0}; the lower slope had a modal class from $20\text{-}30^{0}$ and ranged from 10^{0} to 60^{0}. She suggested that the large number of back wall angles which are relatively gently sloping is due to the large number of cirques in her sample from the NW Highlands formed on Torridonian sandstone and quartzite.

Although extremely large cirques, such as Walcott cirque in Antarctica (Taylor, 1926), have been reported in a few glaciated regions, the dimensions of the vast majority of well-developed cirques vary within a similar range over widely dispersed areas. The discrete cirques found by Gordon (1977) vary little from those distinguished by Andrews and Dugdale (1971) or Evans (1974), and where variations do occur they can often be largely ascribed to the variations in definitions chosen by the researchers. This study presents values of amplitude and gradient which differ to some extent from those measured on true cirques and studies variations within one glaciated region.

Factors Responsible for Variation in Rock Wall Dimensions

Three distinct sets of factors appear to be responsible for the variation in glacier source wall dimensions observed in the field area; climatological, topographical, and geological. In this section the relationship between rock wall amplitude and area, and climatically controlled factors is discussed. The basic assumption is that the magnitudes of the area and amplitude dimensions of a rock wall are indicative of its degree of development through erosion by incipient glaciers over several occupations by local ice. It is hypothesised that rock walls will be best developed in those areas most favourably located in terms of the regional climatic gradient both through the length of time the site is occupied and the erosional capacity of the ice over unit time.

Rock wall size and climate are related by erosion, or more specifically, abrasion rates exerted by the occupying glacier on its bed, and integrated over time. Boulton (1974) defined the abrasion rate A_b as

$$A_b = (k.N.A.V)/p$$

where A is the apparent area of contact between the debris in the glacier sole and the bedrock surface, N is the effective normal pressure exerted upon the bedrock surface, V is the velocity of the debris in the glacier sole, p is a measure of rock hardness and k is a constant that depends on the relative hardness of the rock debris and the bedrock surface. Over any one rock type, abrasion is a function of N and V only (Olyphant,

1977) and these variables depend on ice thickness, itself dependent on the glacier mass balance. Therefore locations which have the largest accumulation rates and smallest ablation rates should have the greatest rock wall development.

Several studies have been carried out with the object of assessing erosional rates of cirque glaciers (e.g. Andrews, 1972a; Andrews and LeMasurier, 1973; Reheis, 1975). Reheis (1975) calculated erosion rates that were very high ($4920-8160mm.yr^{-1}$) on the Arapaho Glacier, Colorado Front Range and assumed that because the mass exchange (the sum of winter and summer balances of accumulation and ablation, integrated over the glacier surface (Paterson, 1969, p.31) is large, conditions are and were favourable for maximal cirque erosion. By implication this would also be true for rock development due to floor lowering. In a discussion of erosion rates under various climatic regimes Anderson (1978) noted that temperate glaciers '...may produce 2 to 10 times more debris than subpolar glaciers'. He expected to find, on Baffin Island, that glaciers at lower altitudes would have the highest erosion rates because of increased englacial temperatures. However, this was only partly true due to the interaction of other factors, not least of which is the influence of glacier size.

From these consideration there are two aspects of the glacier mass balance which are important to the erosion rate and rock wall development. Firstly, ice thickness is dependent on maximising accumulation and minimising ablation. In the study area a suitable model is the reconstructed maximum extent of the Loch Lomond Advance glaciers. Sissons (1979c) inferred from morphological evidence that precipitation values varied widely across the Highlands of Scotland during this partial glaciation; this is in agreement with the distribution of rock walls in the area. The evidence indicates that the largest accumulations of ice occurred in the west, decreasing eastwards across the

Highlands. A secondary trend was noted by Sissons and Sutherland (1976) in the SE Grampians: here accumulations of ice decreased northwards and northwestwards from the Highland Boundary. Thus, assuming ablation did not vary in precisely the same systematic manner as accumulation, the thicknesses of ice initiated against rock walls decreased in the same directions as noted above from accumulations. According to Boulton's theory abrasion rates (and consequently rock wall development) should vary systematically in the opposite direction, and the largest rock walls should be found in the west, SW and SE of the study area.

Secondly, the sum of accumulation and ablation is important. This would again favour western locations, with not only the overall greatest precipitation totals but also the greatest ablation rates due to atmospheric advection, in summer from the Atlantic Ocean, bringing warm air and rain most often to this area. The only alternative summer moisture source is the North Sea: the pronounced development of the Main Lateglacial Shoreline on the east coast of Scotland (Sissons, 1974b) indicates that the surface of the North Sea thawed in summer during the Loch Lomond Stadial and hence, probably, during earlier similar periods of partial glaciation. In order to account for the group of well-developed cirques which face south in Glen Clova and which contained glaciers during the Loch Lomond Stadial, Sissons (1979c) argued that increased cloudiness rather than precipitation was the result.

Spatial Variations in Rock Wall Dimensions

In this section regional spatial variations in rock wall dimensions are described. To analyse regional differences the total population of former glacier source walls was divided into the six regions (Chapter 2), frequency histograms were

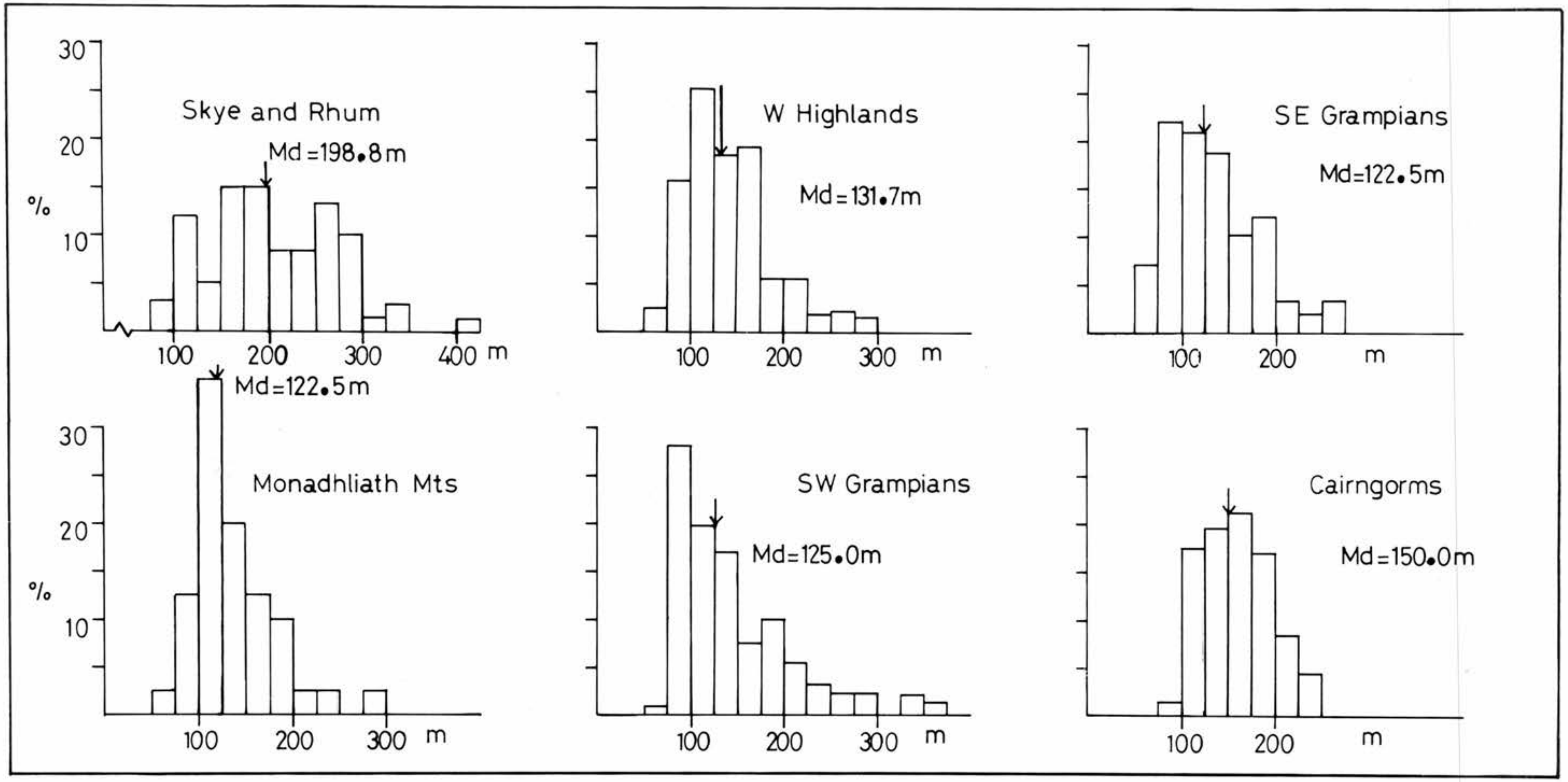


Fig. 4.4 Variations in rock wall amplitude between Regions

constructed for amplitude and area as shown in Fig. 4.4 and Fig. 4.5 and analysis of variance tests carried out. Secondly, amplitude and area were treated as continuous spatial variables and trends in their values sought using multiple regression techniques.

Rock Wall Amplitude

Fig. 4.4 indicates that the amplitude distributions tend to be positively skewed. The median amplitude for each region is shown in Table 4.1. Median values for four of the six regions

Table 4.1 Dimensions of Former Glacier Source Walls

	Amplitude (m)			Area (km^2)	
Region	n	median	range	median	range
SE Grampians	58	122.5	63.3-255.3	0.2052	0.0478-1.1775
Cairngorms	47	150.0	83.0-246.4	0.2403	0.0604-1.1658
W Highlands	161	131.7	56.0-289.2	0.1775	0.0287-1.1532
SW Grampians	93	125.0	62.5-400.7	0.2104	0.0321-2.0159
Skye and Rhum	59	198.8	77.8-472.9	0.2867	0.0524-2.7693
Monadhliath	40	122.5	74.0-292.8	0.1396	0.0355-1.1763

are very similar, the SE Grampians, SW Grampians, Monadhliath Region and the West Highlands having median values within a range of less than 10m. The median value for the Cairngorm Region is a little larger, and that for Skye and Rhum much larger. A Kruskal-Wallis analysis of variance by ranks test was applied to the data to assess the statistical significance of the variation in amplitude by region (Siegel, 1956, pp.184-94). This test, the non-parametric equivalent of the F-test, does not analyse the data values themselves but rather considers their rank order so that skewed distributions may be investigated.

The test yielded a value of H = 52.34, which with 5 degrees of freedom (the number of regions less 1), gives a probability less than 0.001 under the null hypothesis. With 0.05 taken as an acceptable level of significance, the alternative hypothesis that the amplitude values do not all belong to the same population was accepted.

The actual variations in distributions between regions may suggest why these variations exist. Fig. 4.4 indicates that the distribution of amplitude in the Skye and Rhum Region includes many extremely large features, while the minimum values are similar to elsewhere. However, in the Cairngorm Region the total range is shifted towards higher values while the positive skew is decreased so that this area has the largest minimum but also the smallest maximum amplitude values of any region. Skye and Rhum contain a wide range of amplitude values, no one class containing more than 16% of the values, whereas the Monadhliath Region has a modal class (100-125m) containing over 35% of all the values.

Although there are variations in regional amplitude values, the distributions suggest that to some degree this dimension of former glacier source walls varies as much within regions as between them. Multiple regression analysis was carried out to assess any overall trend in amplitude development. This was done using the SPSS Multiple Regression procedure (Nie et al., 1975). In order to satisfy the requirements of the test, a square root transformation was carried out on the skewed amplitude data. The two independent variables employed were the coordinates locating the midpoint of each former source wall, the National Grid alphabetic characters being replaced by numbers and grid values corrected to true north. The linear trend equation given by

$$\mathrm{AMP}^{\frac{1}{2}} = -0.0011\ \mathrm{EAST} + 0.0002\ \mathrm{NORTH} + 12.5648$$

was obtained, where $AMP^{\frac{1}{2}}$ is rock wall ampltiude, and EAST and NORTH are grid values in the x and y directions of the coordinate system respectively. The linear surface explained 6.81% of amplitude variation and, with a multiple correlation coefficient (R) of 0.2610, was significant at the 0.001 level (Blalock, 1969, p.465). The partial correlation coefficient between $AMP^{1/2}$ and EAST, controlling for NORTH is -0.2568 which is significant at the 0.001 level. The results indicate that amplitude increases significantly in a westerly direction.

The addition of terms to form a quadratic equation to the above linear trend equation improved the level of explanation to 11.47% yielding

$$AMP^{1/2} = -0.5600\times10^{-2}EAST + 0.1515\times10^{-5}SQE + 0.1504\times10^{-2}NORTH$$
$$- 0.1687\times10^{-6}EASNOR - 0.4401\times10^{-7}SQN + 12.4242,$$

where SQE and SQN are respectively the square of easting and northing and EASNOR is twice their product. The multiple correlation coefficient of 0.3383 is significant at the 0.001 level. Fig. 4.6 indicates the direction shown by the linear and quadratic trend surfaces, the minimum values of the quadratic surface occurring in the centre of the field area.

Rock Wall Area

Rock wall area varies markedly between regions. The Kruskal-Wallis test yielded H=22.78, which is significant at the 0.05 level. Table 4.1 and Fig. 4.5 show similarities with amplitude in that the rock walls with the largest areas tend to be located on Skye and Rhum. The Monadhliath Region has the smallest rock wall areas, and with the SE Grampians has the

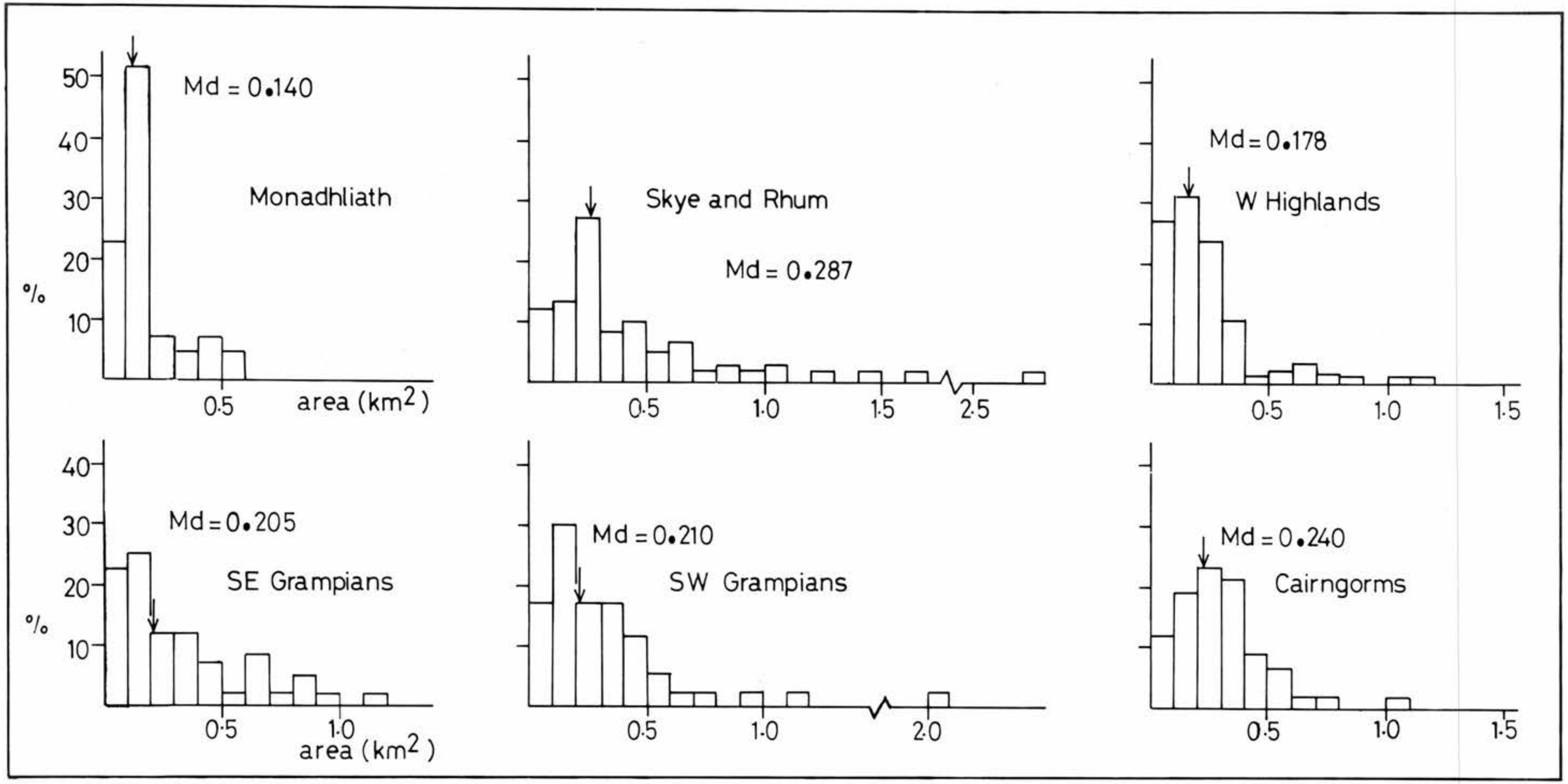


Fig. 4.5 Variations in rock wall area between Regions

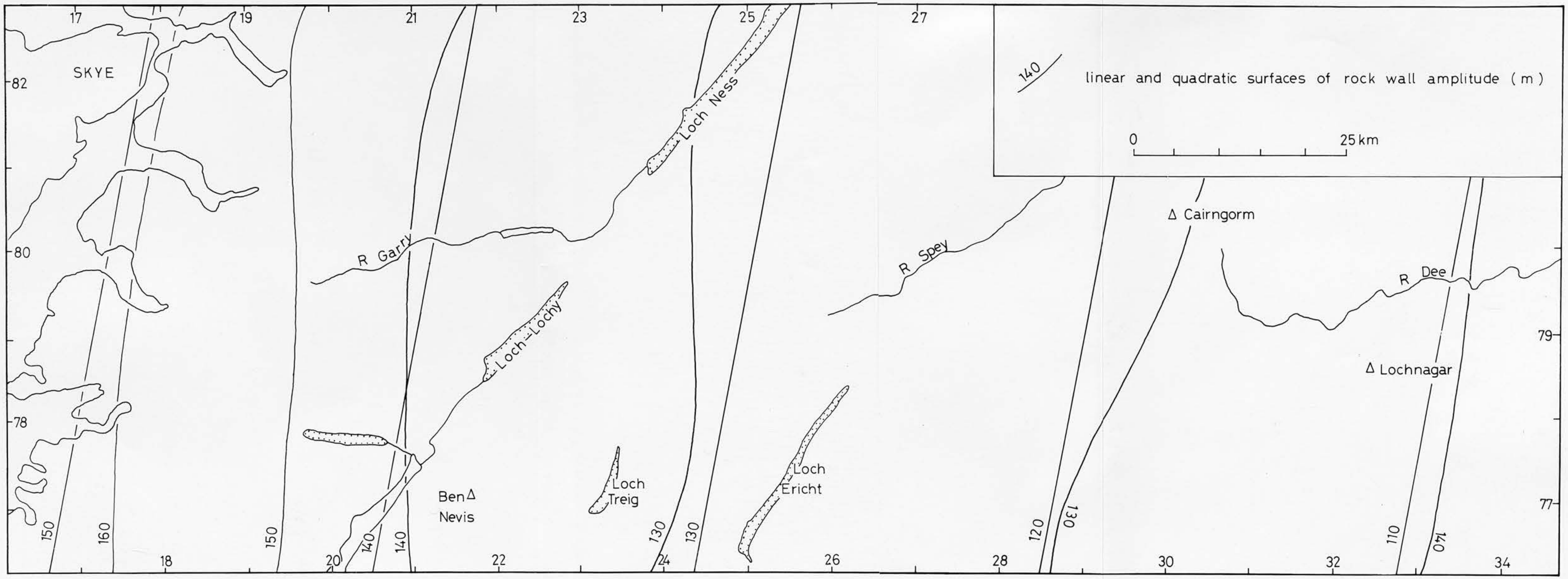
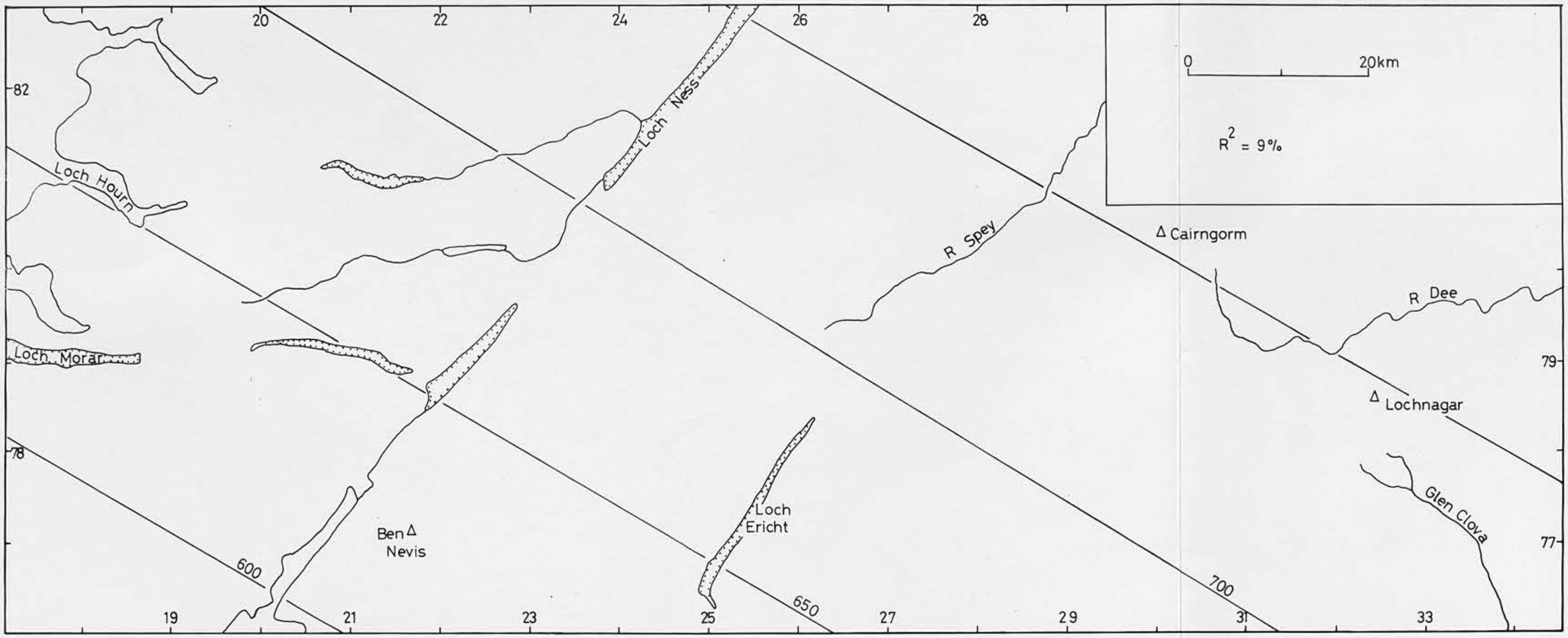
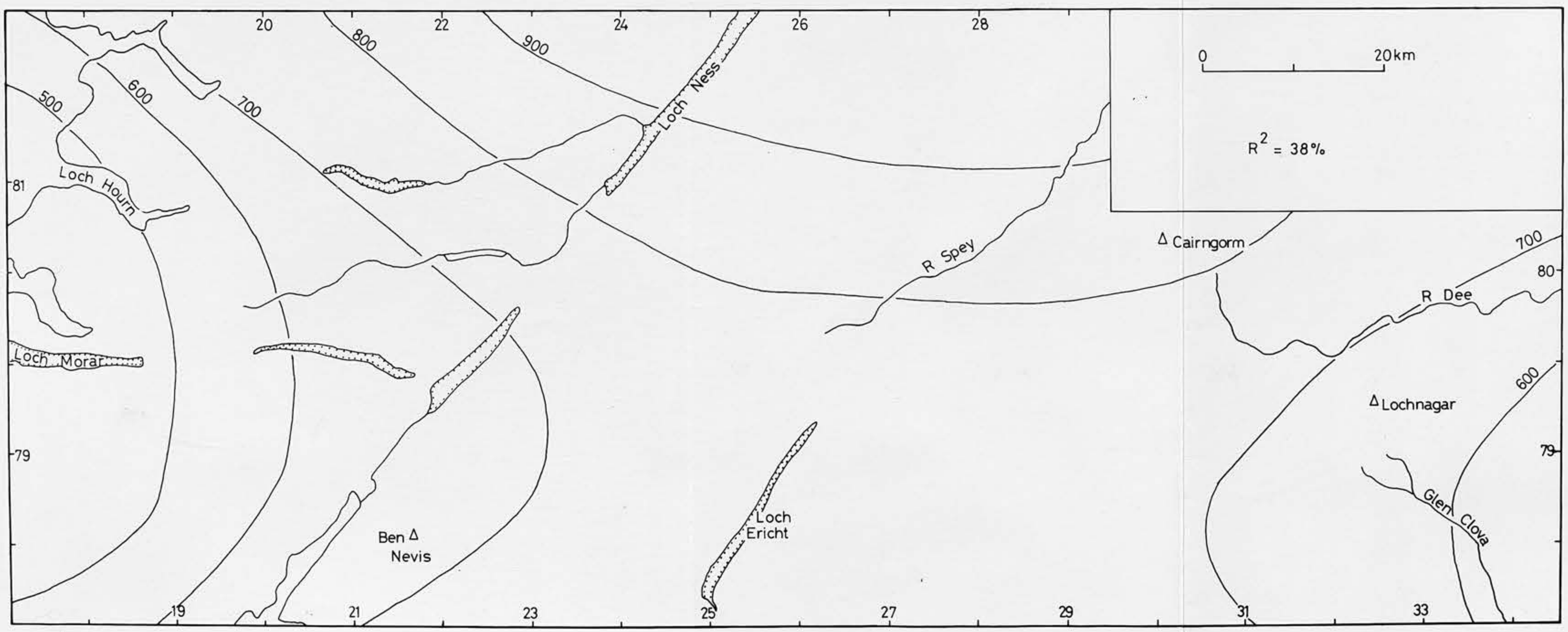


Fig. 4.6 Trend in Amplitude across the Study Area



0
20km
R^2 = 9%
Loch Hourn
Loch Ness
Loch Morar
R Spey
Cairngorm
R Dee
Lochnagar
Loch Ericht
Ben Nevis
Glen Clova
600
650
700
20
22
24
26
28
19
21
23
25
27
29
31
33
82
78
79
77



0
20km
R^2 = 38%
Loch Hourn
Loch Ness
Loch Morar
R Spey
Cairngorm
R Dee
Lochnagar
Loch Ericht
Ben Nevis
Glen Clova
500
600
700
800
900
20
22
24
26
28
19
21
23
25
27
29
31
33
81
80
79

lowest median amplitude. The West Highland Region does not contain very large rock walls, although it has a high rock wall density (Fig. 3.9), suggesting the area is suitable for glaciation. Its lack of large walls suggests that the initial assumption of a correlation between favourable location and size is not always true, and that other factors are relevant. The alternative is, that they have not grown by destroying the divides and side walls between them. Multiple regression analysis was carried out as with amplitude, the linear and quadratic surfaces explaining 0.21% and 6.63% of the variation in area respectively. The quadratic surface is significant at the 0.001 level with n=458, although it explains very little of the variation in rock wall area. Thus although vertical development of glacier source walls increases with a westerly location, lateral extension of the wall does not necessarily follow.

The findings of the locational survey of rock walls may be summarised as follows;

(i) rock walls on Skye and Rhum are the best developed in the study area, exhibiting a large range in both amplitude and area;

(ii) on the mainland, there is a tendency for well developed rock walls to occur in the Cairngorms, although this region does not contain the largest amplitudes or areas;

(iii) although the amplitude of rock walls in the West Highlands may be large, areas tend to be small, and this is not due to high density since the densest distribution occurs on Skye and Rhum where rock walls are also largest;

(iv) the Monadhliath Region has a very narrow range of amplitudes and areas, and they tend to be small; the median rock wall area is less than half that for Skye and Rhum.

To some extent the observed pattern of glacier source wall dimensions is compatible with the erosion theory presented above. Rock wall amplitudes show a clear trend of increasing size towards the west and SW; although this was not found to be so for rock wall areas. Analysis of variance showed significant differences among the topographic regions, and the distribution patterns of both amplitude and area in these regions suggest some relationship with westerly location. Rock walls in Skye and Rhum on the western margin of the field area are certainly the best developed and those in the Monadhliath Region tend to be the poorest; these are respectively the best and least well-placed regions in terms of the inferred precipitation gradient.

However, evidence from elsewhere does not support this argument. The West Highlands and SW Grampians both exhibit high densities of rock walls (Chapter 3) and it was inferred from this that the areas were well-suited to glacial accumulation, but although some large forms do occur (notably around Ben Nevis) the majority of source walls tend to be small. On the other hand, in the Cairngorms the glacier source walls are larger than average but this is an area not well favoured for glacial accumulation. The SE Grampians lie immediately to the south of the Cairngorms and in terms of the deduced moisture supply during periods of cold climate were much more advantageously placed for the accumulation of ice and snow from direct precipitation, but here the glacier source walls are less well developed vertically and laterally, indicating little direct relationship between rock wall development and the climatic gradient. So far this theory of cirque floor lowering and its extension to the development of former glacier source walls has been discussed with no reference to geological differences and it may be that lithology is obscuring the systematic variation in rock wall development due to the climatic effect on erosion. The effects of geology will be discussed in the following section.

Two factors broadly related to the climatic pattern may serve to disrupt the direct relationship considered above. Firstly, there is the problem of interference by external ice in the erosional activity of ice related to a rock wall source. The situation may be envisaged where ice and snow accumulated below a rock wall on a valley side and moved out from the rock wall. At its junction with the valley ice stream, the velocity of the smaller volume of ice arriving from the rock wall source would have been impeded, and stress normal to this ice flow increased. In his theoretical interpretation of erosional mechanisms under ice based on both observation and experimental work, Boulton (1974) has related the abrasion rate to effective normal pressure exerted by ice, for any velocity. He showed that there is always a pressure above which deposition rather than abrasion occurs and that the lower the velocity, the lower the normal pressure required. Although this is not proven, a logical extension, _ceteris paribus_, is that, where a glacier occupies a valley along which its flow is uninhibited, abrasion rates will be highest, but where ice flow is impeded as envisaged above, erosion along the floor will be reduced, and thus the amplitude of the rock wall itself will not be increased by floor lowering.

The second factor can be inferred from the distribution of former glacier source walls across the study area as indicated in Chapter 3. This suggests that locations that were most favourable in terms of the precipitation gradient for cirque glaciers were also the areas where the most severe erosion of the entire land surface occurred and rock walls are largely absent.

If the distribution of ice masses at the Loch Lomond Stadial maximum (Sissons, 1979a) is assumed to be comparable to that of many periods of partial glaciation and the build-up to ice sheet maxima during the Pleistocene, then the West Highlands area may have been disadvantaged relative to other regions for much of the time when elsewhere glaciers beneath rock walls were eroding. The West Highlands has been suitable for the accumulation of large amounts of snow and ice but rock walls are not particularly well developed. With many glacial troughs cut through from the Great Glen to the west coast, it is not unreasonable to suggest that in this area, ice flow from rock wall source areas (which frequently form recesses along the sides of major troughs) would, for long periods, have been impeded by ice streams eroding the troughs. At the other extreme, rock walls on the islands of Skye and Rhum would have benefited from little interaction at their sources with other ice streams; at the stadial maximum glaciers radiated from the mountains of these islands, some reaching as far as present sea level (Sissons, 1977; Ballantyne and Wain-Hobson, 1980). Rock walls in the Cairngorms would also have tended to have glaciers isolated from other ice streams. However, since few glaciers extended at this time far from their source area (Sissons, 1979b) this does not seem a sufficient reason for their good development. This area was also disadvantaged in terms of the total through-put of ice and snow and also ice thickness. Other reasons must be sought to account for the normal distribution of former glacier source wall amplitudes and areas in this region and their relatively large size.

In summary, although the regional climatic gradient and climatically related factors may account for the location of the large glacier source walls on the islands of Skye and Rhum they are not sufficient reason to explain the distribution on the mainland and the large differences between the islands and neighbouring mainland rock walls. Other factors must be invoked to account for the overall better development of rock walls in the Cairngorms than either the SW or SE Grampians, and for the large variations found in these regions.

The Effects of Geology on Rock Wall Dimensions

There is much confusion in the current literature about the importance of rock type in cirque development. In the last section it was noted that location relative to the inferred climatic pattern did not explain shape and size variations satisfactorily, since there is often as much variation within small areas as between them. Although geology, other than by its influence on topography generally does not determine where source walls are situated it may determine how well they are developed, by for instance, the exploitation of lines of structural weakness.

Cirques, and by analogy, glacier source walls tend to be best developed on igneous rocks and poorest on sedimentary strata (Embleton and King, 1975, p.208; McCabe, 1939). However, beyond this there are several contradictory views on the influence of rock type. On the one hand, in the Jotunheim, an area of fairly homogeneous lithology, Battey (1960) found an immense variety in cirque form, and concluded that geology was unimportant in the development of the cirques. Similarly, Jennings (1952) found great asymmetry in cirque erosion on Snaefell (East Iceland), a mountain composed of stratified basaltic lavas, tuffs and breccias. Harker (1901) found that gabbro, lavas and dykes in the Cuillins were all eroded to a common level to form smooth rock surfaces on the cirque floors. In the Bridge River District of British Columbia, Evans (1974) found that cirques showed little relationship to lithological contrasts. 'Variations in jointing within each rock type, varying relief and topographic situation, and position with respect to former glaciers seem to be more important controlling variables' (Evans, 1974, p.136).

On the other hand, in a study of thirteen cirques in NW Sutherland, Thompson (1950) concluded that cirque formation was related to the distribution of Lewisian gneiss and quartzite. He found that head walls are well developed on the quartzite compared to the gneiss where development depended on the existence of shatter planes. Temple (1965) found that cirques in the Lake District are best developed along structurally weak zones but that they have been eroded indifferently across the Skiddaw slates, Borrowdale volcanics and granophyre. McCabe (1939) found stratigraphic control on cirques in strata dipping at 2° so that the strata with higher resistance formed platforms.

In an extensive study of cirque forms in Swedish Lapland, Vilborg (1977) concluded that although rock type does not affect cirque development, the characteristic structure of certain rocks does. In schistose rocks, fracture planes are the principle planes of weakness and they influence cirque development. However, in rocks that tend to break up under pressure release, such as granite and quartzite, rock disintegration may occur with ice movement.

Haynes (1968) considered the influence of rock structure and particularly the joint plane angle on the shape of cirque long profile. In igneous rocks such as Cairngorm granite she found a tendency for joints at medium angles to cirque floors to exist, along which the ice moved causing an elongation of the back wall foot zone. Elsewhere she identified sets of high and low angled joint planes which have interacted to form steep upper head walls and more gently sloping bases. Structure may also influence cirque head wall aspect (e.g. Haynes, 1968; Derkson,1976; Vilborg, 1977).

In this study former glacier source walls are examined in terms of their suitability as sites of glacial accumulation; interest is not in how structure controls rock wall development per se, since this has been considered in many studies such as those mentioned above. Interest is rather in assessing the influence of geology on the variation in shape and size of rock walls where these variations might elsewise be attributed to the efficacy of glacial erosion. This is particularly important in view of the initial assumption that rock wall size is diagnostic of rock wall development. Since the study area covers a variety of rock types it is necessary to discover how they contribute to rock wall dimensions. Olyphant (1977) considered that relationships between cirque morphometry and location have not been detected because the effects of varying lithology have not been taken into account (e.g. Trenhaile, 1976). His paper is open to criticism, however, since he only considered local factors in his study of the depth of cirque erosion.

Each former source wall in the study area was assigned to one of six major rock categories (see Chapter 2) and in addition, the last and newer granites were subdivided into five divisions depending on their location. Fig. 4.7 and 4.8 show the medians and ranges of variability in amplitude and area between rock types. Dalradian quartzite tends to contain the poorest rock walls and has the narrowest range of amplitudes (76.0-177.9m). The non-granitic igneous rocks have the best developed and also the widest range (75.0-472.9m). This concurs with the broad variations given in the literature cited above.

Because of the skewed distributions of amplitude and area non-parametric tests were employed to discover any statistically significant relationships between rock type and rock wall dimensions. Kruskal-Wallis one-way analysis of variance by ranks was applied to test the null hypothesis that the six rock types were derived from the same population of area and

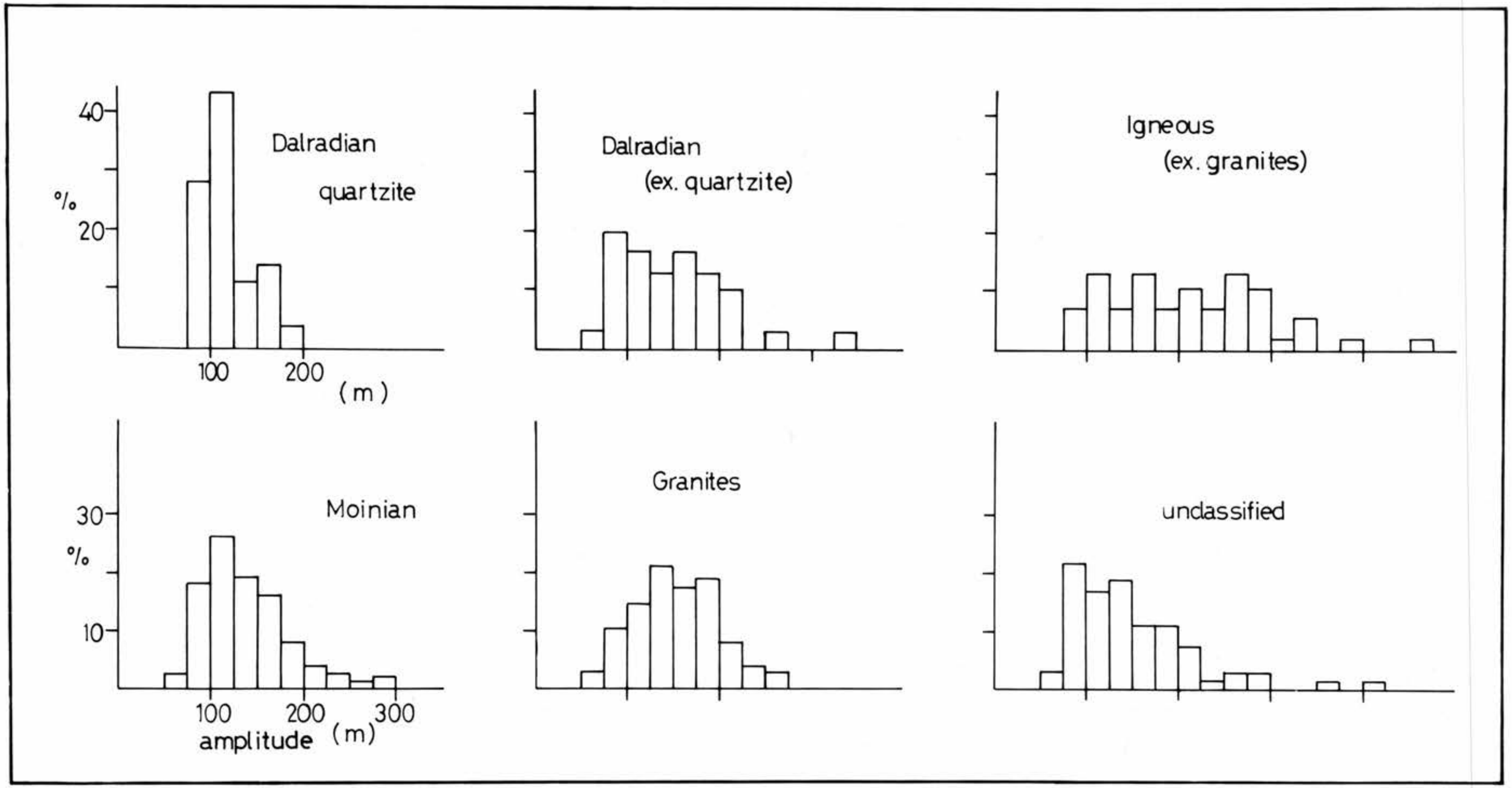


Fig. 4.7 Variation in Amplitude with Rock Type

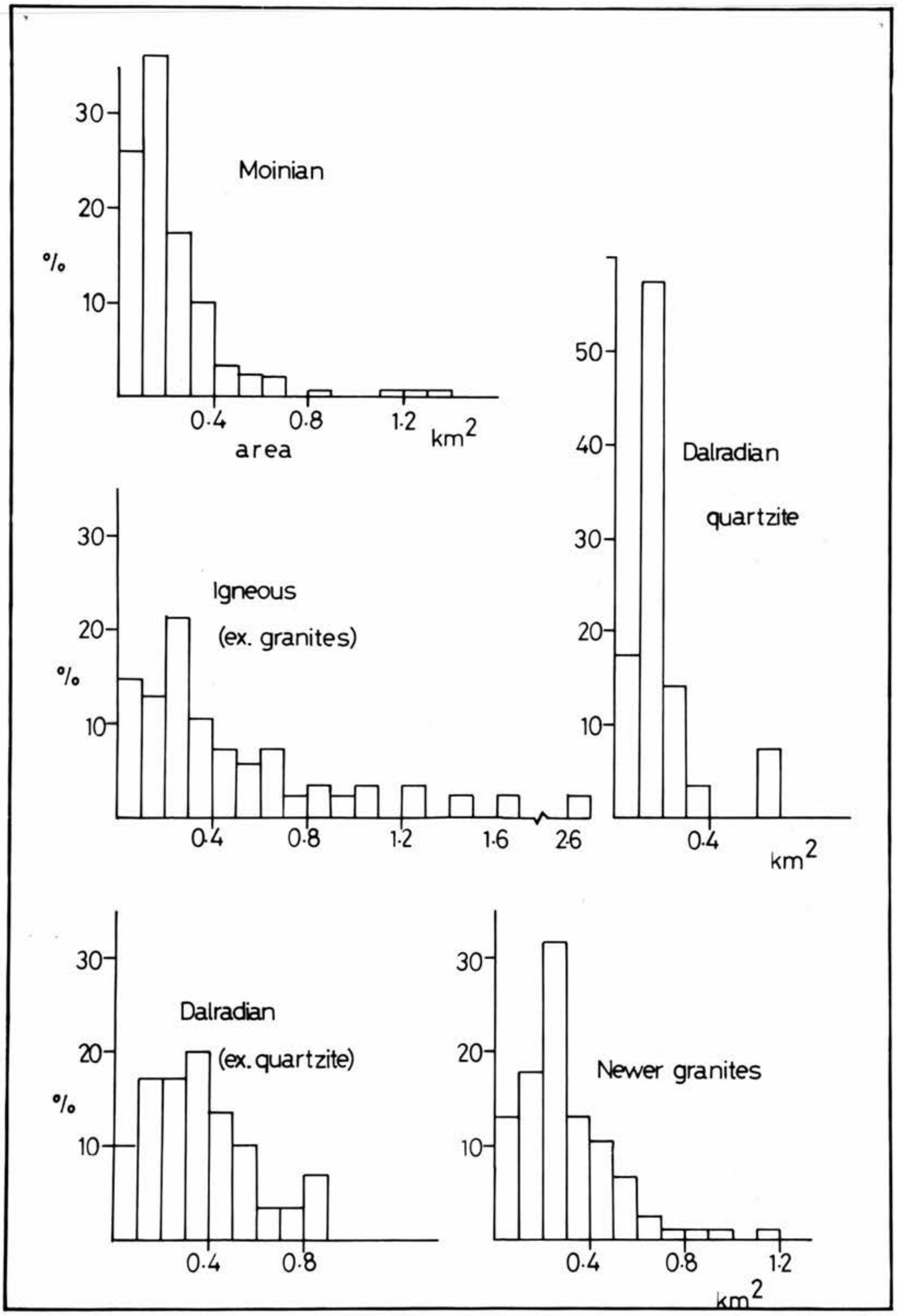


Fig. 4.8 Variations in Rock Wall Area with Rock Type

amplitude. Table 4.2 indicates that the null hypothesis can be rejected, and that the six rock tyes have amplitudes and areas that vary from each other at the 0.05 significance level. However, over small areas this is not always so. Only the SW and SE Grampian Regions contain a wide variety of rock wall lithologies. For each of these the above test was carried out on rock wall amplitude and geological categories. In the SW Grampians (n=93), H=8.0904 with 3 degrees of freedom was found to be significant at the 0.05 level; in the SE Grampians (n=46) with 4 degrees of freedom, H=2.1176 which is not significant.

Table 4.2 Variation in Amplitude and Area with Geology

		Amplitude (m)		
Rock Type	n	median	minimum	maximum
Moinian	205	128.2	56.0	292.8
Dalradian quartzite	28	114.4	76.0	177.9
Dalradian ex. quartzite	30	143.2	66.7	325.0
Granites	74	150.0	70.0	265.0
Igneous ex. granites	43	203.1	75.0	472.9

H=55.572, d.f.=4, $p < 0.001$

	Area (km^2)		
Moinian	0.1577	0.0288	1.3431
Dalradian quartzite	0.1454	0.0444	0.6885
Dalradian ex. quartzite	0.3357	0.0667	0.8243
Granites	0.2045	0.0550	1.1656
Igneous ex. granites	0.3151	0.0524	2.7692

H=49.412, d.f.=4, $p < 0.001$

To some extent Figs 4.4 and 4.7 are similar (as are Figs 4.5 and 4.8). The West Highland Region contains 161 rock walls of which 140 are found on Moinian metamorphics consisting of banded pelitic and psammitic schists (Johnstone et al., 1969). Using a Mann-Whitney U test (Siegel, 1956, pp.116-27) no significant difference in amplitude was found between the Moinian rocks west and east of the Great Glen (sample sizes 140 and 65 resectively).

Rock wall amplitudes in the igneous rocks of Skye and Rhum are significantly larger than those on non-granitic igneous rock elsewhere as indicated by a Mann-Whitney U test (sample sizes 47 and 8 respectively, significant at the 0.05 level). This is consistent with the islands having the best developed rock walls as indicated in the last section. Since this is the area (as considered above) in which would be expected the best developed rock walls due to climatic and climatically related factors, such as external ice movement, it is difficult to ascertain the separate influence of the two sets of factors. However, rock walls are cut in granites both in Skye and in less climatically favoured areas. The granite of the SE Grampians crops out on Lochnagar and Mount Keen, on the northern margin of the region. A Mann-Whitney U test was applied to test if the rock walls cut in granite in Skye and Rhum had statistically significantly greater amplitudes than those in the SE Grampians. With sample sizes of 10 and 11 respectively, a U value of 24 was obtained indicating that the granite of Skye and Rhum yields larger rock walls than in the SE Grampians at the 0.001 significance level. Thus although the best developed rock walls in all areas occur on igneous rocks, the significant differences in their size between the Islands and elsewhere suggest that rock wall type is not the only factor operating but that the climatic and climatically related variables are also important.

The best developed rock walls in the field area occur on gabbro. This is in direct contrast with the poorly developed, easterly, low-lying cirques in Swedish Lapland cut in gabbro and basic volcanics, which '... are considered to be conspicuously resistant to cirque erosion' (Vilborg, 1977, p.122). Battey (1960) commented that the ultrabasic rocks of the Jotunheim, although olivine-rich, resisted erosion better than the metamorphics, attributing this to the inhibition of chemical weathering by low temperatures and, relative to the surrounding rocks, their lesser susceptibility to frost-riving.

It is unlikely that the development of large rock walls in gabbro is due to the greater susceptibility of this rock to chemical weathering (Hatch et al., 1961, p.495) in preference to other rocks during interglacials, since during the time that has elapsed since deglaciation, chemical weathering has been virtually non-existent. This is evidenced by the abundance of well-preserved striae in the Cuillins and particularly in the Coruisk valley. Harker (1901), for example, based much of his study of the glaciation of the Cuillins on the evidence of striae.

A much stronger argument may be presented for the enhanced development of rock walls in the Cuillins of Skye through largely mechanical erosion by ice in terms of their maritime location, topography and independence from mainland ice. All these factors combine in this region to produce the maximum accumulation of snow and ice against rock walls and erosion of them. This argument is substantiated by the evidence from rock walls occurring on granite: rock walls formed of granite on Skye are significantly larger than those composed of granite in the east of the study area. It is concluded that the occurrence of the best developed rock walls on gabbro is a coincidence and that they are largest here because of the factors enhancing generally mechanical erosion by ice during glacial periods.

The least well developed rock walls in the study area occur on Dalradian quartzite. Although quartzite is chemically inert (Ollier, 1969, p.83) it can be disintegrated rapidly by frost action. It is probably this factor more than any other which accounts for the poor development of rock walls in this rock.

A possible additional factor affecting rock wall amplitude on quartzite is that this rock occurs consistently at high altitudes. Later in this chapter rock wall amplitude is shown to be negatively related to its basal altitude; hence if the basal altitudes in quartzite tend to be high, this might lead to a spurious correlation between this rock and small glacial source walls. In fact, this is not so. In the SE Grampians the rock walls formed of quartzite tend to occur on the higher mountains (median=1035m compared with 870m for all other rock types, significantly different at the 0.001 level) and they also have higher base altitudes (mean=808.8m and 663.4m respectively, significant at p=0.005). This suggests that although there is a greater opportunity of increased amplitude through their existence on high mountains it is not displayed.

Anderson (1978) commented that the variations in rock type ought to be taken into account when analysing the contribution of other factors. The simplest way to do this is to eliminate geological variation by considering the other effects over one rock type. Since only granite and Moinian rocks occur widely over the study area, multiple regression analysis was carried out on the square-root of amplitude over these two rock types separately, using the same variables as previously. On the granite rocks explanation of the variation in the transformed rock wall amplitude improved from R^2 of 11.47% to 20.81% for 74 cases with a multiple correlation coefficient of 0.4562, significant at the 0.01 level.

A similar regression analysis was conducted over rock walls formed on Moinian rock only, however, no significant result was produced. This is consistent with the argument expressed earlier that Moinian rocks produce source walls which do not vary significantly in size east and west of the Great Glen, because rock walls composed of Moinian rocks are often located close to locations of other ice bodies.

The Effect of Topography on Rock Wall Development

Topography may affect the development of glacier source walls in several ways distinct from the rock type in which they are formed. It may act in two ways to enhance or impede rock wall formation. The first effect is simply that the greater the depth of relief, either in terms of the summit altitude or the difference between summit and valley altitudes, the greater is the possible amplitudinal development. Altitude also affects climate: higher altitudes have greater precipitation and lower temperatures and therefore have a greater likelihood of the accumulation of ice and snow. Rock wall area is not considered in this section since it is difficult to see how it should vary altitudinally except as it varies with amplitude, although is may vary with the massiveness of the mountains. This is not quantified.

The first of these altitudinal effects on amplitude is straight forward, assessing the extent to which rock wall amplitude is simply an expression of the relief amplitude above the level at which glaciers can exist at any time. A Spearman rank correlation test (r_s) was used to evaluate the relationship between rock wall amplitude and mountain height. With 458 rock walls this yielded $r_s = 0.1173$, which is not significant at the 0.05 level, indicating that with this crude measure there is little relationship between the two parameters.

Since it is apparent that rock type does affect rock wall development the test was carried out again for each rock type category in the study area. The results are shown in Table 4.3. Over Moinian and the non-granitic igneous rocks there is a significant relationship between amplitude and mountain height. Dalradian quartzite gives the surprising result of an inverse relationship, albeit poor, perhaps because the summit altitudes were not required to be of the same rock type as the rock wall.

Table 4.3 Correlation between Amplitude and Summit Altitude for each rock type

Rock Type	n	r_s	significance
Moinian	205	0.1931	0.003
Dalradian quartzite	28	-0.2109	N.S.
Dalradian ex. quartz.	30	0.2425	N.S.
Granites	74	0.1671	N.S.
Igneous ex.granites	43	0.4379	0.002

The good correlation between amplitude and mountain height for non-granitic igneous rocks may be because in these areas (e.g. the Skye Cuillins) the rock wall crest often forms the drainage divide.

A second way of assessing this relationship is to study altitude in terms of the amplitude of relief in the immediate vicinity of the rock wall, relief amplitude being the altitude difference between each summit and neighbouring valley. Although on Skye and Rhum altitude and relief amplitude are more or less the same, this is not always so on the mainland. The Cairngorms were chosen to test initially for any relationship between rock wall amplitude and relief amplitude since this is the highest inland area. No significant relationship was found and this form of analysis was not pursued. It is apparent that, in general, rock wall amplitude expresses more than the height of the mountain on which it is situated.

The second effect of altitude is more difficult to formulate. Olyphant (1977) constructed a working hypothesis that cirque floor lowering (of which rock wall amplitude is a numerical expression) is influenced by altitude and aspect due to their effects on climate and hence on glacier mass balance. Hence an increase in altitude increases erosion of the cirque floor and leads to an increase in cirque floor lowering. Olyphant used summit altitude rather than basal altitude to assess this since variations in summit altitude reflect not only temperature changes with altitude, but also shading. His comment that summit altitude affects shading is not strictly true. It is ground slope angle relative to solar altitude that controls shading and this is dependent on, among other things, the difference between summit and floor altitude, that is, the amount of floor lowering that has already occurred. In fact, by using summit altitude Olyphant unwittingly combined altitudinal and aspect effects in one factor and then employed aspect again as another supposedly independent variable.

Another formulation of the hypothesis was presented by Anderson (1978), who expected to find an inverse relationship between erosion rates and altitude (this time above the equilibrium line) for glacial cirques on Baffin Island. He suggested that this would be because the glaciers at lower altitudes should have higher englacial temperatures. However, his study showed no such relationship, the glaciers at higher altitudes also having southerly aspects and therefore, Anderson believed, also having higher englacial temperatures. Put more simply, he found that increased melting on south-facing slopes is aided by increased precipitation at higher altitudes to produce more active glaciers.

It appears that considerable care is required in formulating any hypothesis relating rock wall amplitude and altitude. Favourable and unfavourable aspects should be considered separately so that the confounding effects of varying solar energy receipts are avoided. The assumption that erosion rates depend on englacial temperature is unjustified since they depend rather, on the basal ice temperature. In a temperate glacier the basal ice is considered in theory to be at pressure melting point (Paterson, 1969, p.168). Only the accumulation zones of maritime glaciers (e.g. Blue Glacier in Washington State (LaChapelle, 1961)) can be said with certainty to be temperate (Shumskiy _et al_., 1964). Since the field area is located in a maritime region pressure melting at the base of former glaciers may be assumed. Thus the hypothesis proposed by Anderson between altitude and glacier source area erosion is not suitable.

A hypothesis that states that amplitude increases with floor altitude is clearly inoperable at high altitudes. In fact, overall there is a negative relationship between floor altitude and rock wall amplitude, taken separately over favourable (NW, N, NE, E) and unfavourable aspects, both r_s values being significant at the 0.005 level. Further to the reported results that aspect and altitude are both significant (Olyphant, 1977) and that equilibrium line altitude is not as important as aspect in erosion of rock walls (Anderson, 1978), the variation of rock wall amplitude with mountain aspect was considered. Table 4.4 shows the range of variation with different aspects of all rock walls. It shows that rock walls that face south or SE tend to be much larger than those facing north although those facing west are smallest. In order to be sure that these aspects are not correlated with other variables that affect rock wall amplitude (e.g. rock walls of a particular aspect might be mainly of one rock type, or occur in one locality), a significance test was carried out on rock walls occurring only on one rock type and across only one region. To simplify the

Table 4.4 Rock Wall Aspect and Amplitude

Aspect	n	Amplitude (m) median	min	max
North	124	132.1	70.0	327.1
NE	123	139.4	56.0	342.2
East	94	137.0	66.7	400.7
SE	28	156.0	62.5	472.9
South	15	153.6	94.0	365.0
SW	9	134.0	90.0	343.5
West	14	118.0	77.5	396.1
NW	31	124.3	75.7	258.3

test the rock walls were divided into two groups, composed of those with a southerly component of direction (unfavourable) and those with a northerly component (favourable), west and east being included with the first and second groups respectively. Mann-Whitney U tests were carried out on several groups of data (in the SE Grampians on Dalradian rocks excluding quartzite; in the SW Grampians on quartzite, and also on other Dalradian rocks; on Skye and Rhum over non-granitic igneous rocks) and these did not exhibit any significant differences between the amplitude of rock walls having favourable and unfavourable aspects.

It is apparent that in the study area, there is not a straight forward relationship between the amplitude of rock walls and the aspect and altitude at which they occur. Obviously, if the summit altitude is low, rock wall height may be restricted. For example, a rock wall, although poorly developed, exists on the north side of Meall Doir' an Daimh (N.G. ref. NN168970), at an altitude of 580m with mean amplitude of 86.0m in Moinian psammites. On the other hand, in Coire na

Craoibhe on the east-facing side of Glean na Guiserein, Knoydart (N.G. ref. NG753036), where the summit altitude is 520m, a rock wall of mean amplitude 162.5m is developed on the same rock type. Similarly, where the summits are high, rock walls may have large amplitudes, but this is not always the case. However, if summit altitudes varied more widely over the study area (the range is only some 820m, excluding a very poor rock wall developed at 330m) the tendency for rock wall amplitude to increase with altitude might be more apparent.

The Slope Angle of Glacier Source Walls

The slope angle of former glacier source walls was seen earlier not to vary greatly. There is no a priori hypothesis to suggest that slope angle should vary in a spatially systematic manner. The very small variations in slope angle between regions are apparent from Table 4.5. The SE Grampians have the overall lowest value and also the lowest mean. The rock wall

Table 4.5 Regional Variations in Rock Wall Slope Angle

Region	n	x^o	S.D.
SE Grampians	58	35.63	4.66
Cairngorms	47	37.56	3.64
West Highlands	161	38.86	4.31
SW Grampians	93	37.12	4.69
Monadhliath	59	37.84	3.13
Skye and Rhum	40	38.62	3.51

with the steepest slope is on Carn Dearg in the SE Grampians. It seems most likely that these differences are attributable to rock type variations rather than spatial variations.

Analysis of variance applied to the slope angle data showed that there are variations in angle with rock type, the F-ratio of 8.884 being significant at the 0.001 level. The variations are shown in Table 4.6. Dalradian quartzite contains the most gently sloping rock walls, while non-granitic igneous rocks support the steepest. However, although this rank order of rock type is maintained to some extent over smaller areas (the SE and SW Grampians) only in the SW is the F-ratio significant (Tables 4.7a and b).

Table 4.6 Variation in Rock Wall Slope Angle with Geology

Rock Type	n	$\bar{x}^o$
Moinian	205	38.77
Dalradian quartzite	28	34.35
Dalradian ex. quartzite	30	36.31
Granites	74	36.76
Igneous ex. granites	43	39.0
Others	63	37.23

Analysis of Variance

Source	d.f	S.S	M.S.	F-ratio	p
Between Groups	5	761.85	152.37	8.884	<0.001
Within Groups	437	7495.11	17.15		
Total	442	8256.95			

One possible non-lithological factor that might have a bearing is whether or not the rock wall was sharpened up by occupation during the Loch Lomond Stadial. This cannot be a major factor over most of the field area since the morphological evidence suggests that almost all the rock walls were source areas for glaciers (see Chapter 3; Sissons, 1979a). However, in

Table 4.7a Rock Walls Gradient and Rock Type in SE Grampians

Rock Type	n	slope angle
Moinian	5	36.44
Dalradian quartzite	10	33.31
Dalradian ex. quartzite	14	34.97
Granites	11	35.57
Igneous ex. granites	6	36.00

Analysis of Variance

Source	d.f	S.S	M.S.	F-ratio	p
Between Groups	4	48.43	12.11	0.540	0.7071
Within Groups	41	919.11	22.42		

null hypothesis accepted

Table 4.7b Rock Wall Gradient and Rock Type in SW Grampians

Rock Type	n	slope angle
Moinian	23	36.63
Dalradian quartzite	18	34.93
Dalradian ex. quartzite	15	37.57
Granite	9	35.83
Igneous ex. granites	2	38.75

Analysis of Variance

Source	d.f	S.S	M.S.	F-ratio	p
Between Groups	4	364.82	91.20	5.540	0.0007
Within Groups	62	1020.74	16.46		

null hypothesis rejected

the Cairngorms this was not so. On the granite Sissons (1979b) mapped the evidence for 16 glaciers (the seventeenth was located on the Moinian) of which 15 had rock walls at their source. A Student's t test was carried out to see if there are significant differences in slope angle between those rock walls where glaciers were nourished during the Stadial and those where there is no such evidence. With sample sizes of 19 and 23 respectively and $\bar{x}_1 = 38.24$ and $\bar{x}_2 = 36.83$ a t value of 1.2068 was obtained which was not significant at the 0.05 level. The null hypothesis was thus not rejected and it was concluded that there is not enough evidence to suggest that occupation by the last ice is a contributory factor to slope angle variation.

The great similarity in slope angles across the field area at around 35-39^{0} may be related to the most common angle of repose of snow and firn in the accumulation area of a glacier. The slope of a complete cirque glacier can vary quite widely. For example, using the inventory provided by the Atlas of Glaciers in Southern Norway and Northern Norway (Østrem and Ziegler, 1969; Østrem et al., 1973), slope angles of less than 10^{0} and greater than 60^{0} are recorded for cirque glaciers, but are commonly between 20^{0} and 30^{0}. The author has not been able to find data for the source area alone on present day glaciers.

Discussion

Rock type has played an important role in influencing the development of glacier source walls in the field area, although it is not always the over-riding variable. All the factors (climatic, topographic, and geological) tend to have favoured the development of rock walls on the islands on the western margin of the study area. Here are the most favourable locations in terms of meso-scale climate; the mountains are high with radiating valleys; the igneous rocks that form the mountains accommodate very high, steep cliffs and may have been greatly dissected before being inundated by ice.

Nowhere on the mainland do all these factors work together, apart from certain individual instances where they combine to produce well-developed rock walls. For example, over much of the SW Grampians, Moinian or Dalradian metamorphics are exposed in rock walls. However, around Ben Nevis granite and other igneous rocks form the bedrock and summit altitudes and relief amplitudes are high. During the Loch Lomond Stadial the western end of the summit ridge and the Mamore Forest ridge contained several glaciers (Sissons,1979c). However farther east in one south-facing rock wall there is no evidence for stadial glaciers (Thorp, 1979) and accordingly it seems that the western ends of these ridges were particularly favoured in terms of the precipitation gradient; it is here that very large rock walls are developed. Eastwards along the ridges, rock walls tend to be formed in Dalradian quartzite and schists, those in the quartzite being the least developed.

In the West Highlands rock wall bedrock is almost entirely Moinian schists, which nowhere seem to produce large rock walls, even although the area is on the western margin of the landmass, and has a high density of rock walls. However at the other extreme the granites of the Cairngorms contain many large, steep rock walls at high altitudes, but no extremely large forms occur here, in an area not well placed for receiving precipitation.

Conclusions

Several general conclusions can be drawn from the analysis carried out on the former glacier source walls in the field area.

1. Down-cutting versus headwall erosion

Little variation in amplitude with mountain elevation suggests that backward erosion of the rock wall is pre-eminent over down-cutting below the wall. A large relief amplitude tends to have little effect on amplitude. This disagrees with White (1970) who suggested for rather unconvincing reasons that down-cutting was the dominant process. The present study cannot answer this problem fully however, since no measurements have been taken of the longitudinal extension of the source area with increasing amplitude.

2. Density and rock wall development.

There is no direct relationship between density and the size of rock walls. In the West Highland Region there is a high density of rock walls, suggesting that there are many suitable locations for accumulation and thus a climate favourable to glacier source areas. However, rock walls are not large here, indicating that the lateral walls between them have not been eroded. Whether this is an inherent feature as concluded by Gordon (1975), or is a function of other factors is unknown. On Skye high density and large rock walls occur together, the high density resulting from the radiating nature of the rock walls around the Cuillins.

3. There is not always a straight forward relationship between the amount of floor lowering (as represented by rock wall amplitude) and local or regional factors of climate, topography and geology. A multiple regression between the square root of amplitude and mountain altitude, rock wall base height and location in a quadratic plane, over granite rock and favourable aspects only, explained only 23.43% of the variation in this parameter across the study area.

CHAPTER 5

THE SPATIAL DISTRIBUTION OF ROCK WALL ALTITUDES

Introduction

This chapter is concerned with the variation in altitude of former glacier source walls across the field area. Following a discussion of factors that affect rock wall base altitude the altitudinal distribution is analysed. As in previous chapters the extensive literature on cirques is drawn upon.

The altitude of glaciation

It has long been accepted that cirque floors lie close to the altitude of the local firn line and orographic snowline at the time of cirque erosion (Cotton, 1942, p.182; Flint and Fidalgo, 1964), the best review of the early literature being given by Charlesworth (1957, pp.296-7). In many studies the position of the regional snowline during glaciation has been estimated from generalised surfaces of cirque altitude (e.g. Ljungner, 1949, pp.36-9, Hastenrath, 1971). By considering how the elevation of the estimated snowline varies across a glaciated region for which meteorological data have been collected, the relationship between the climatological and glaciological systems may be analysed. By comparing the present snowline surface with a reconstructed one palaeoclimatic inferences may be made, albeit generally on a simplistic level. For example, Porter (1964) examined the case where the snowline is closely related to precipitation. He argued naively that if the present snowline is paralleled by a former lower one, the depression of the snowline ensued from a fall in mean summer temperature, but if the lines (or surfaces) intersect, variations in the precipitation pattern are also likely. Basic problems encountered with this approach to understanding cirque altitudes are (i) the precise nature of the snowline, (ii) the relationship between the altitude of glacierization and cirque altitude and (iii) the interpretation of snowline altitudes in climatic terms.

The Concept and Definition of the Altitude of Glacierization

Many authors have attempted to define the altitude of glacierization (in common nomenclature the snowline) believing it to have intrinsic significance for glacial studies. Ahlmann stated that the regional snowline

> '. . . is one of the most important of the climatological features from which a true appreciation of the geographical properties of glaciers and of conditions governing their existence can be gained.' (Ahlmann, 1933, p.187)

The significance of the snowline lies in its ability to define the boundary between glaciated and non-glaciated areas. The boundary can be measured however, in several ways. Flint (1957, p.48) defined the climatic snowline as the '...average lower limit of perennial snow' and, believing it to be controlled entirely by climatic conditions (rather than by local factors such as topography and orientation) used it as a synonym for the regional snowline. Andrews and Miller (1972) were more precise. They preferred to think of the climatic snowline as '...the lower limit of perennial snow on fully exposed, nearly flat surfaces' (p.47); they stated that the regional snowline does not merely reflect major topographic influences and, in their view, the climatic snowline lies above the regional snowline. This interpretation suggests that the climatic snowline is an unmeasurable concept. Studies attempting to relate the dynamic glaciological and climatological systems must take into consideration the topographic situation and its effects on the regional snowline through local factors.

Østrem (1966) summarised methods of determining snowline altitudes which can be quantified. He reintroduced the concept of the Glaciation Level (GL) (a term used here in preference to the Glaciation Limit to avoid confusion with the spatial extent of glaciers) from the work of Brückner (1887, translated by Østrem, 1966). This defined the GL as the mean altitude of neighbouring summits that contain glaciers and those that do not. The GL was used by Ahlmann (1948, Fig. 31) to indicate the elevation of glaciation around the north Atlantic coasts and has subsequently been used by Østrem (1966, 1972), Andrews and Miller (1972) and, Miller et al. (1975) to obtain the lower limit to glaciation in parts of the Canadian Arctic and the Rocky Mountains.

The equilibrium line that divides a glacier into its accumulation and ablation areas may also define the boundary between glaciated and non-glaciated areas. Above the equilibrium line the glacier has a net gain of mass over the year; below it there is a net loss (Müller, 1962). Averaged over a period of years the Equilibrium Line Altitude (ELA) approaches a steady-state if the climate is stable. This value is slightly lower than the conceptual ELA on neighbouring snow-free ground because of the cooling effects of ice on the lowest layers of the atmosphere. The steady-state ELA of small cirque glaciers may be adjusted to recent climatic events while larger glaciers are still responding to past regimes (Miller et al. 1975). Miller et al. (1975) calculated both ELA and GL indices for Queen Elizabeth Islands, N.W.T., Canada. Contour maps of the measurements were similar, the ELA lying 100-200m below the GL. Averaged over an area the ELA most closely represents the regional level of glaciation (i.e. the regional snowline). The difference in elevation between the ELA and GL is a function of differences between the local and regional climate and local and regional topographic controls (Miller et al. 1975).

These quantities which are direct measures of the altitude of glaciation cannot be employed in presently unglaciated areas. The indirect methods most commonly used are related to cirque altitude (e.g. Unwin, 1973) or the altitude of firn lines of former glaciers reconstructed from morphological evidence (e.g. Sissons,1974a; Ballantyne and Wain-Hobson, 1980).

Cirque Altitude and the Altitude of Glaciation

The nature of the relationship between cirque floor altitude and the orographic snowline has been discussed by several authors. Flint (1957, p.101) considered cirques to lie just below the orographic snowline. Andrews and Miller (1972) disagreed: they postulated that the orographic snowline is delimited by the lowest perennial snowpatch which may or may not occur in a cirque, and so the orographic snowline may lie below the cirque floor. The present author agrees with the latter view particularly since many cirque glaciers extend well beyond their cirque source and terminate far below the cirque floor altitude. Moreover, the equilibrium firn line altitude may be below that of the cirque floor. An example of this is found in the study area where glaciers of the Loch Lomond Advance extended far below their cirque sources. In the Cairngorms where Sissons (1979b) mapped the glacier limits and estimated equilibrium firn lines, the rock wall base altitude is generally below the reconstructed firn line. However in some cases the relationship is reversed. A glacier that was supplied from three coalescent cirques (with well-developed rock walls) between Braeriach and Cairn Toul (NGR NN959986) extended for more than 1km down the Dee Valley. Its equilibrium firn line altitude was estimated at 897m (Sissons, 1979b) compared with a mean rock wall base altitude of 991m.

Trenhaile (1975) gave both the glaciation level and trend in altitude of cirque floors in the Canadian Cordillera but failed to compare them adequately. He showed the linear surfaces connecting cirque floors rises inland in the same direction as the GL and with a similar gradient. Unfortunately, the difference in elevation between the measures was not given for individual locations.

The local altitude of glaciation clearly does not form a consistent relationship with cirque altitude. However, along with the GL and ELA altitudes it is a quantifiable expression of the glaciological system: it is the result of interactions between the individual glacier, the regional climate as it is displayed locally and the surrounding topography.

Local Variation in Cirque Altitudes

The altitudes of individual neighbouring cirques vary for two main reasons. Firstly, cirque altitudes commonly rise toward the centre of a mountain group demonstrating a topographic effect bearing no relation to the regional level of glaciation (Derbyshire and Evans, 1976). Cirque altitudes share this feature with ELA's and GL's (Miller et al. 1975).

The second factor that contributes to the variation in cirque altitudes over short distances is the effect of aspect on the position of the orographic snowline. In many areas a direct relationship between altitude and aspect has been found whereby (in the Northern Hemisphere) cirques facing south and west are at higher altitudes than those facing north and east. This is due to several regional and local interacting effects which are fully described by Evans (1974, 1977). These effects may be summarised here as the result of two variables that often act towards the same result. South- and SW-facing slopes receive the greatest amounts of direct insolation and summer melting is encouraged, while accumulation is often greatest on slopes in the lee of the prevailing wind. These are generally the east- or NE-facing slopes.

A classic example of these effects is the 'Ural type' cirque glacier, found by Dolguishin (1961) in the Polar Urals, where accumulation of wind-blown snow into lee slope concavities is sufficient to maintain active glaciers, although the climatic snowline lies well above the highest summits. Manley (1959) reported some cirques in the Lake District at altitudes well below the regional snowline during glaciation because of the increased opportunity for snow-drift at the sites.

Although there is a lack of south- and SW-facing cirques in Wales, Seddon (1957) found that the altitude of cirque moraines rises progressively away from a minimum for NE-facing glaciers. Goldthwait (1970) treated aspect and altitude together in a study of cirques in the Presidential Range, New Hampshire, and found that while no cirques face SW, the lowest cirques face north and the highest south, elevation being measured at the intersection of the back wall and floor. Trenhaile (1975) found that cirques in the Canadian Cordillera facing between NW and east are often more than 100m lower than those facing south between SE and SW.

In many respects the ELA and GL vary locally in the same manner as cirque altitude, responding to the variations in climate with orientation and the effects of topography. However, they are time-specific indicators of the interactions between climate, topography and glacier dynamics unlike cirques which represent many periods of glacial erosion. Recent studies of erosion rates beneath cirque glaciers suggest that it may take 30,000-50,000 years of ice occupation to form a cirque (e.g. Andrews, 1972; Anderson, 1978). Therefore cirques are not adjusted to one set of environmental conditions but have been eroded by various ice bodies which may themselves have been accumulated under different combinations of precipitation, temperature and general circulation of the atmosphere and oceans. Cirque glaciers have formed in the same location repeatedly. Once a cirque is formed it enhances the accumulation of snow through sheltering by the rock walls and it is conjectured that the erosion of rock walls increases the shade afforded from the sun.

The hypothesis that cirque stairways and tandem cirques are formed in response to slightly varying climatic conditions seems unlikely. Nonetheless, Miller (1961, 1975) described a fivefold sequence of cirques in the Alaskan-Canadian Boundary Range for which he could find no other control. He claimed that the cirque altitudes were controlled by the relationship between elevation and mean freezing level. This interpretation implies a fine readjustment of the erosion level with climatic variation. On the other hand Fuller (1928) reported cirques at several levels in the mountains of Colorado and Montana and related them to the juxtaposition of rock strata of varying resistances.

In the Scottish Highlands NW of the Great Glen, Godard (1965) claimed the existence of four cirque levels. In the study area there are few cases of true tandem cirques or stairways. One such location is the complex composed of Lota and Harta corries, Skye (NGR NG470245). However. only Harta corrie was included in this study since the rock wall of Lota corrie did not conform to the requirements in Chapter 2. Cotton

(1942) considered it difficult to differentiate between true cirques in tandem and rock steps.

Regional Variation in Cirque Altitude

With all the possible local variation in cirque altitude it is surprising that regionally cirque altitudes are not randomly distributed, but vary gradually to form a definable surface over large areas. The interpretation of these surfaces is full of problems. Each individual cirque occurs at a certain altitude at about which accumulation of snow and ice has been equal to ablation during periods of cirque erosion. Regionally, the altitude at which accumulation equals ablation varies. Since temperature decreases and precipitation increases with altitude (at least over the altitudinal range of the study area), in an area with less precipitation at a given altitude *ceteris paribus*, cirque altitudes must be higher. This relationship is plausible in temporal as well as spatial terms at least theoretically, and so it is invalid to equate altitude variations solely with summer temperature variation through the atmospheric lapse rate (e.g. Andrews, 1965).

A secondary factor is the dynamic nature of each period of glaciation. In the simplest case the first sites to be glacierized during the deterioration in climate are those where precipitation just below summit altitude is sufficient for net accumulation. These sites are in areas which receive most precipitation or are on the highest mountains where lower summer temperatures compensate for regional variations in amounts. As the climate deteriorates further, sites at lower altitudes and those less favourable for precipitation become suitable and the process continues. Meanwhile at the sites that were initially most favoured accumulation may have occurred to such an extent that valley glaciers, piedmont glaciers or ice caps have enveloped the original rock wall glaciers. The original cirques may cease to be eroded. In this case cirque altitudes and locations would mark the succession of sites marginally suited to glacierization. Since this dynamic control of cirque occupation and erosion is dependent on a massive ice build-up largely through precipitation it is of secondary importance to the altitudinal control due to direct precipitation variations.

The simple model of spatial variation in precipitation is complicated by accumulation due to other factors mainly blown snow and avalanching, and ablation due to spatial variation in the importance of warm air advection. Tronov (1962) also suggested that late spring snows at high altitudes may decrease summer ablation while at lower altitudes precipitation falling as rain may accelerate melting.

Summary

Cirques are closely related to the altitude of glacierization when glaciation is marginal in highland areas. Neighbouring cirques may vary in altitude because of topographic and orientation differences that cause important variations in the local climate. They may also vary due to lithological differences, their floors coinciding with more resistant strata. Regionally cirque altitudes vary largely in terms of climate, principally due to precipitation variations that must be compensated by altitude variations for glacierization to be possible. A secondary factor is the availability of sites. In the rest of this chapter variations in rock wall altitudes within and between regions are considered; systematic variations are discussed in the following chapter and local variations in Chapters 7 and 8.

Definition of Cirque Altitude

So far cirque altitude has not been adequately defined: from crest to bottom cirques may cover an altitudinal range of some 200-300m. Various measures have been proposed, Evans (1974, p.142) alone listing nine. Vilborg (1977) considered that the summit altitude of the mountain in which the cirque is incised is most appropriate since cirque erosion occurs when the orographic snowline falls just below summit altitude. However, since the altitude of the snowline may vary on each side of the same mountain this altitude yields less information than one directly concerned with the cirque floor.

Related to the lower boundary of the cirque are the altitude of end moraines, the lip, the mean floor altitude and the intersection between the steep headwall and floor. The altitude of end moraines of former cirque glaciers (as for example used by Seddon (1957) and Unwin (1975a)) is not suitable since it varies for many as yet unidentified reasons, its only merit being that it is not time-transgressive. Cirque lip altitude is also unsatisfactory since the genesis of the lip is not known, and in many cirques it is ambiguous. There is little to choose between mean cirque floor altitude and the altitude of the intersection between the floor and wall. The mean floor altitude however, is often difficult to calculate if the floor slopes, whereas, the head wall-floor intersection is almost always clearly defined. This altitude was used by Porter (1964) and Andrews (1965) and is used here.

The Altitude of rock Walls

Mean rock wall base altitudes in the study area range from 230m to 1154m. The lowest rock wall is associated with a summit altitude of only 330m but is a poor feature close to the NW corner of the study area (NGR NG861165). The highest rock wall is on the SW side of Ben Macdui (1309m) in the Cairngorms (NGR NN987989) and is also poorly developed. The mean rock wall base altitude is 703m $\pm$ 174.2m. The distribution is slightly negatively skewed (Fig. 5.1).

There are large regional variations in rock wall altitudes (Table 5.1). Not only does the highest rock wall occur in the Cairngorms but this area also has the highest regional mean. The West Highlands has the largest range of base altitude values and the Monadhliath Region the least.

Table 5.1 Altitudinal Distribution of Rock Walls (m)

Region	Base (1)	Crest (2)	Summit (3)	(3)-(1)	(3)-(2)
Whole Study Area	703	852	955	252	102
SE Grampians	674	802	895	221	92
Cairngorms	884	1034	1130	250	99
West Highlands	672	810	913	241	103
SW Grampians	801	948	1047	246	98
Monadhliath	756	894	962	205	68
Skye and Rhum	482	691	831	349	140

Fig 5.2 illustrates the distribution of rock wall base altitudes in each region. The West Highlands and the SW Grampians diagrams closely reflect the aggregated pattern of Fig. 5.1 with a slight negative skew and a wide spread of values. The Monadhliath Region has a strongly peaked uni-modal distribution. Elsewhere, the distribution of rock wall base altitudes is bi- or multi-modal.

In preceding sections it was noted that local variations in cirque altitude could not be satisfactorily explained by different climatic regimes since cirques are eroded during

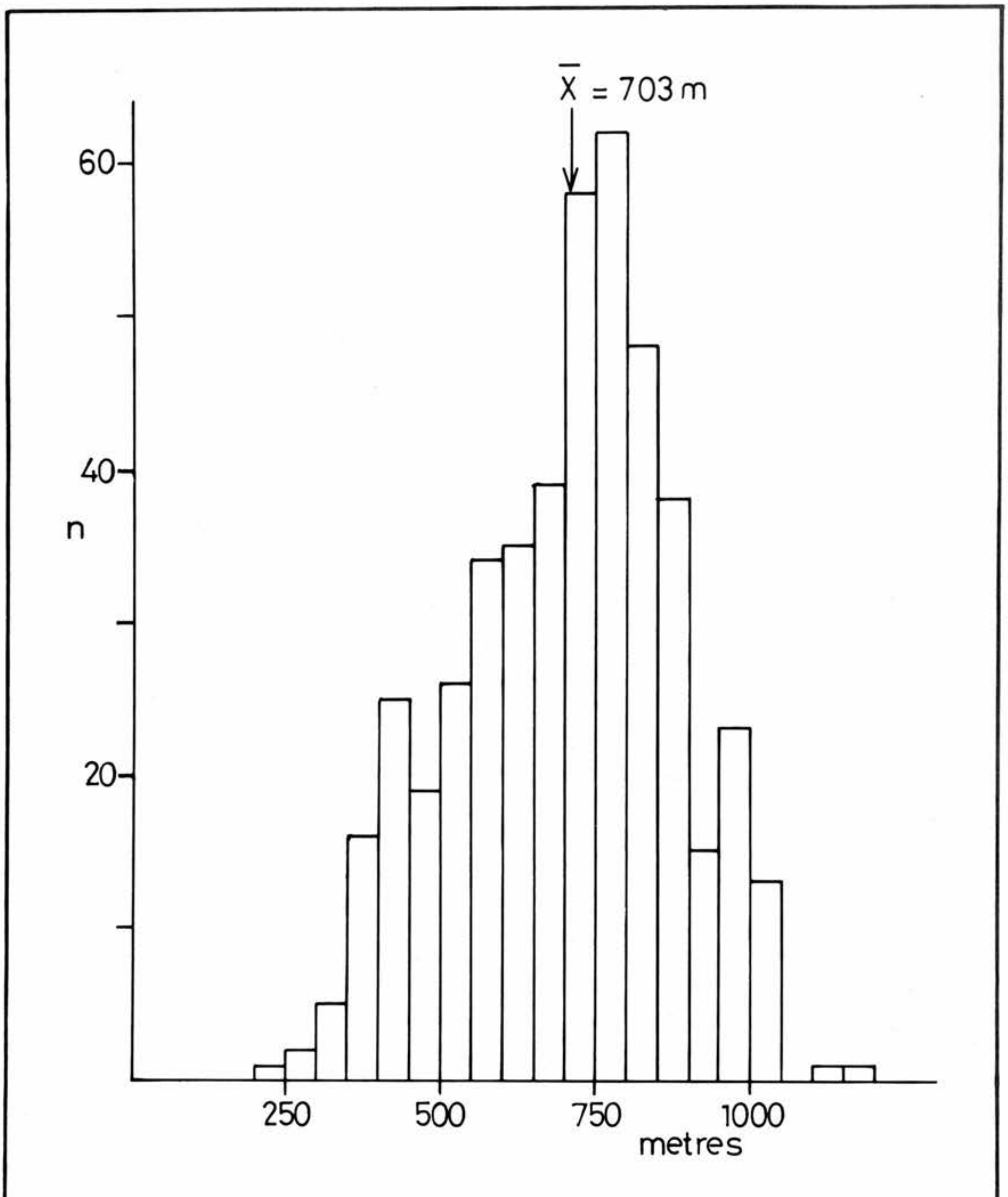


Fig. 5.1 Rock Wall base altitude

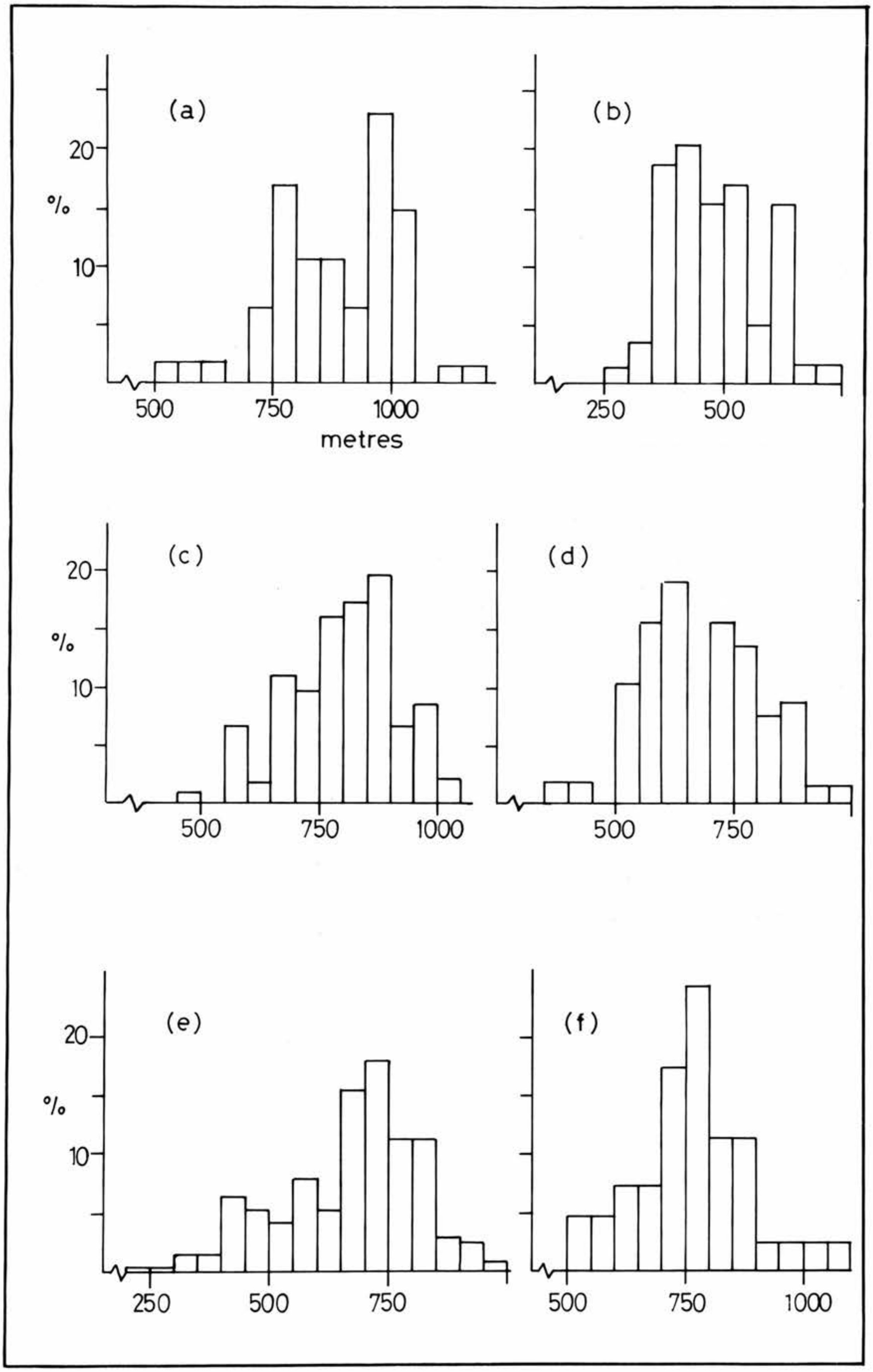


Fig. 5.2 Rock Wall Base Altitude in each Region (a - Cairngorms; b - Skye and Rhum; c - SW Grampians; d - SE Grampians; e - West Highlands; f - Monadhliath Region)

marginal phases of glaciation when the level of glacierization is just below mountain summit altitudes. More reasonable explanations of local altitudinal variations are expressed in terms of

(i) widespread plateau altitudes in the pre-glacial relief,

(ii) bedrock lithology, or

(iii) local variations in the balance between glacial accumulation and ablation.

The third explanation is likely to produce a uni-modal population of varying cirque altitudes whereas (i) and (ii) depend on there being a multi-modal population of actual pre-glacial altitudes or rock strata of varying resistances respectively. (ii) is obviously most complicated when the rock strata are strongly dipping, but if this is so the strata are least likely to be an effective control.

The Altitude of Rock Walls in the Cairngorm Region

The population of rock wall base altitudes in the Cairngorms is strongly bi-modal, the modal groups being 750-800m and 950-1000m. The dispersion diagram (Fig. 5.3) illustrates this clearly with a gap from 880m to 960m in which only three rock walls occur. All but eight rock walls fall within the two groups from 730-880m and 960-1040m. Sugden (1969) also found two groups of cirque altitudes in the western Cairngorms. He proposed that the two groups relate to two separate periods of cirque erosion with the upper group (850-1050m) composed of larger cirques than the lower (600-750m). Plots of rock wall amplitude and area against base altitude revealed no such relationship and the evidence from rock walls does not support his suggestion that the higher rock walls were occupied earlier and for a longer time than the lower ones. Regional variations in the bedrock do not appear to explain the bi-modality in rock wall altitude since all the rock walls are in the Cairngorm granite.

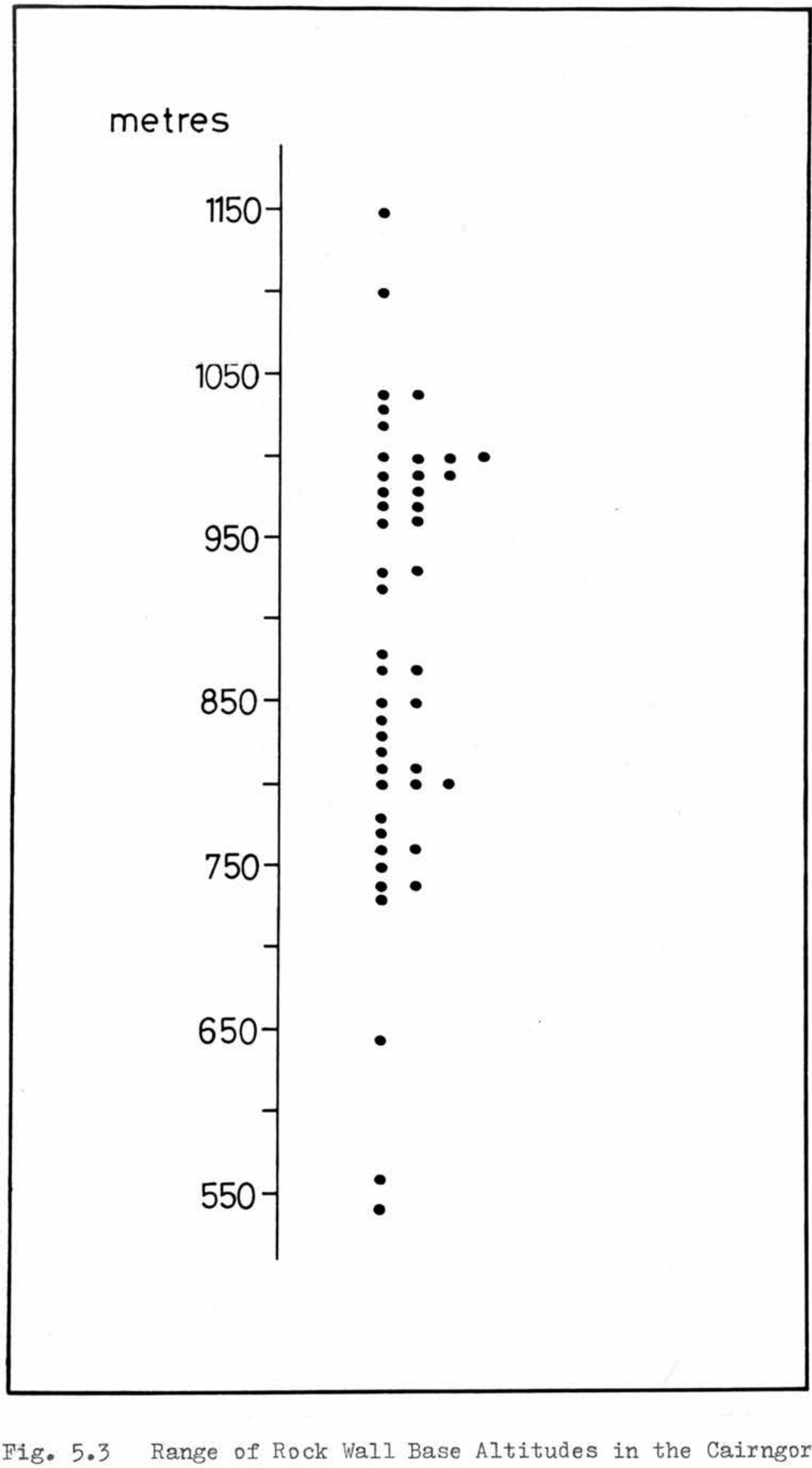


Fig. 5.3 Range of Rock Wall Base Altitudes in the Cairngorms

Several authors have referred to Tertiary erosion surfaces in the study area. Fleet (1938) described a Grampian Main Surface at 730-940m that rises northwards, monadnocks such as the Cairngorm peaks and Lochnagar standing above it. Linton (1951) suggested the existence of a sub-Cenomanian surface tilted eastwards, of which the highest mountain summits in the Grampians are remnants. Sugden (1968) mentioned breaks of slope in the Cairngorms at 760m and 910m and a high surface at 1070-1220m. Although some of the work on erosion surfaces is contradictory, it is useful to view rock wall base altitude in relation to them.

There is a strong correlation between summit altitude and rock wall base altitude, a Pearson's correlation coefficient of 0.93 ($n = 44$, $p = 0.001$) being obtained. The rock walls of the upper group are all located about the highest summits in the Cairngorms. The rock walls bordering the high plateau between Cairn Toul and Braeriach lie above 960m as do those facing east on the flanks of Ben Macdui, Cairngorm and Cairn Lochan. In the eastern Cairngorms the only rock walls belonging to the upper group are those around Beinn a' Bhuird. The mean altitude of the summits related to high rock walls is 1256m $\pm$ 38m compared to a mean summit altitude for the lower group of 1003m $\pm$ 216m. The bi-modal nature of the summit altitudes is illustrated in Fig. 5.4.

The location of the upper group of rock walls 100-200m below the summit surface identified by Sugden (1968) suggests they may be related to that surface. None of the summits below 1170m is related to a rock wall of the higher altitude group. It is not possible to assign the lower group of rock walls to a specific group of summit altitudes since these walls are related to a wide range of summits from 1170m down the 870m.

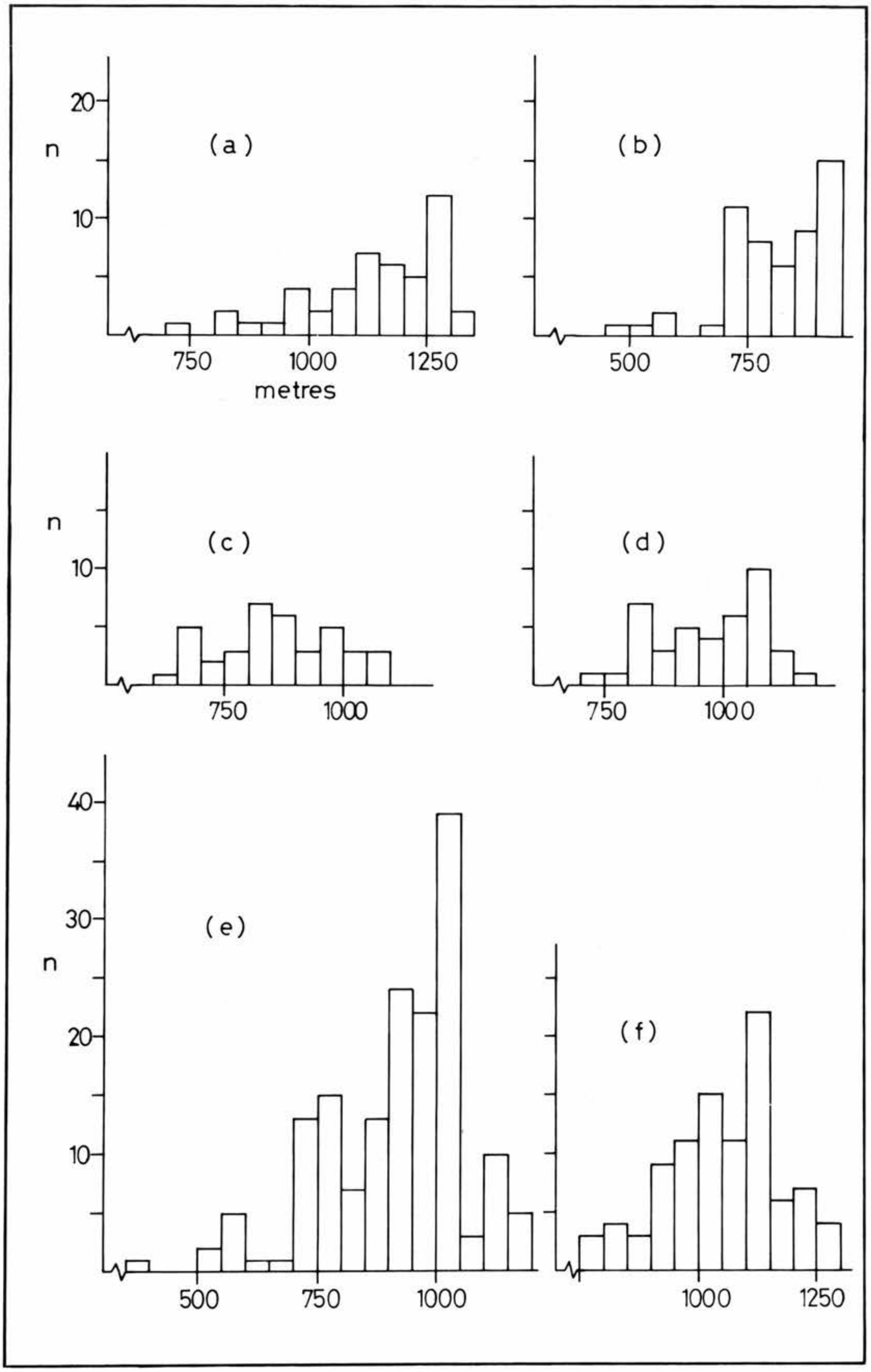


Fig. 5.4 Summit Altitudes upslope from Rock Walls (a - Cairngorms; b - Skye and Rhum; c - SE Grampians; d - Monadhliath Region; e - West Highlands; f - SW Grampians)

Rock Wall Altitude in the SE Grampians

The multi-modality of the SE Grampians is more difficult to interpret. Fig. 5.2d reveals a peculiar pattern that appears to be a normal distribution with one altitude class (650-700m) missing, and two very low rock walls. The low rock walls have been mentioned previously because of the exceptional neighbouring topography that may have facilitated snowdrift allowing glaciers to form at anomalously low levels. The gap from 650m to 700m is surprising and cannot be ascribed to such factors. In parts of the area neighbouring rock walls lie at very similar altitudes. For example, the middle three rock walls on the NE side of Glen Clova (Corrie of Clova, Corrie Brandy, and Corrie Wharral) have mean base altitudes ranging from 640m to 642m. On the opposite side of the valley the rock wall below Hill of Strone (NGR NO297729) has a mean altitude of 644m. Summit altitudes of rock walls in the SE Grampians (Fig. 5.4) are spread over a wide range from 600-1100m with three modes. The highest rock walls are on the Lochnagar plateau that forms part of Fleet's (1938) ancient surface. The rock walls rise towards the NW in roughly the same direction as Fleet's Grampian Main Surface, but this does not explain the gap from 650-700m.

The location and altitude of the rock walls in Fig. 5.2d is plotted in Fig. 5.5. This shows that the rock walls at lower altitudes generally occur towards the Highland Edge and in the SE-facing valleys of Glen Clova, with one each in Glen Isla and Glen Prosen. Very few low rock walls occur on the plateau interior. In contrast, the higher rock walls occur on the northern side of Lochnagar, on the sides of Beinn a' Ghlo and on the plateau interior. Since the Grampian Main Surface rises roughly northwards (Fleet, 1938) and the group of higher rock walls is composed not only of rock walls located on supposed monadnocks above the main plateau surface, but also includes

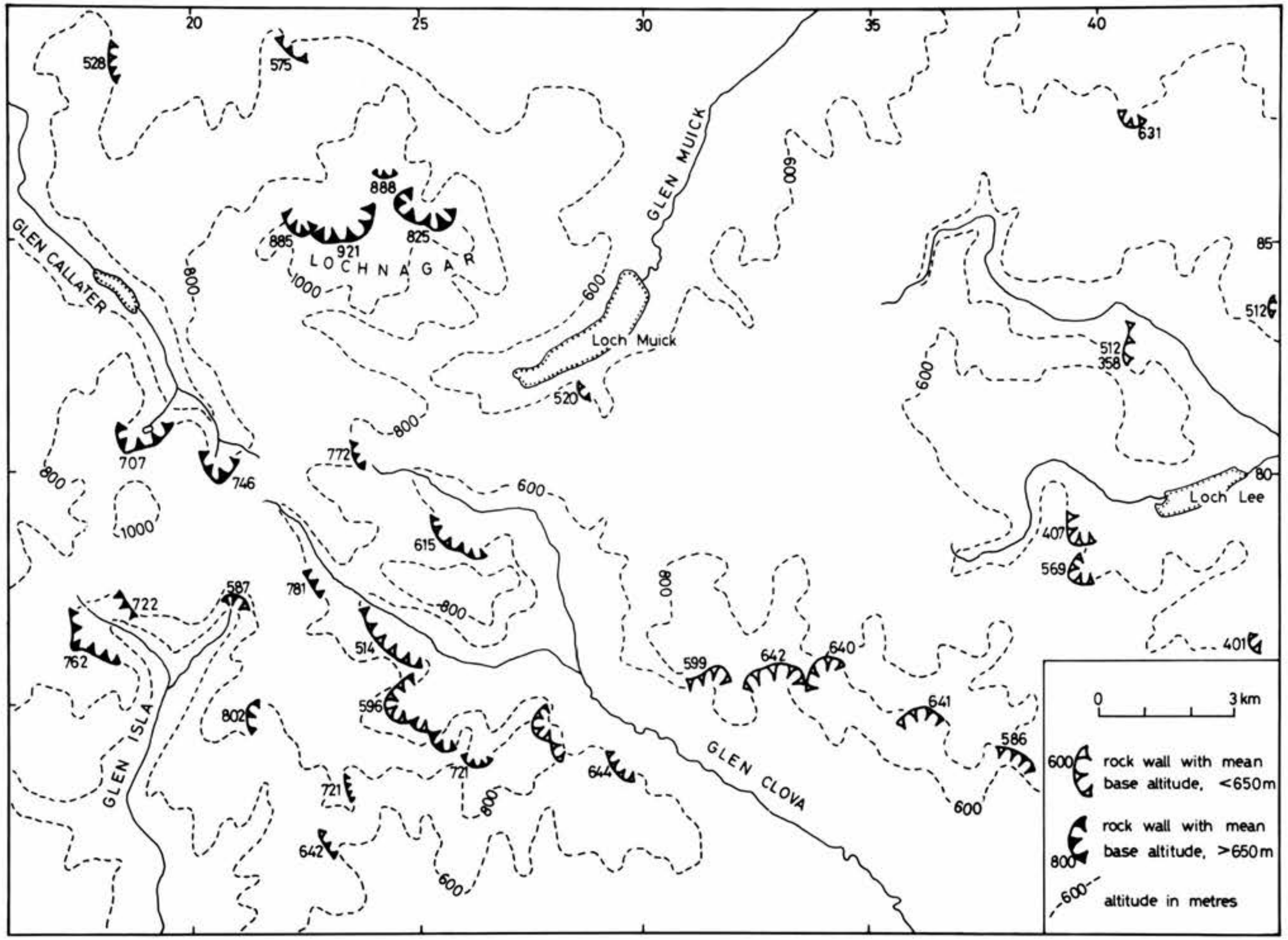


Fig. 5.5 Location and Altitude of Rock Walls in the SE Grampians

some rock walls located on the plateau, the gap in rock wall altitudes between 644m and 701m cannot be considered to divide the rock walls into two separate groups. In addition they could not be two distinct groups since the regions covers a large area over which the climate may have varied greatly.

The altitudes of the rock walls are closely related to summit altitude and it was first supposed that this gap in rock wall altitudes is because there are few summit altitudes between 800m and 900m. To investigate this the maximum altitude within each 1km grid square was noted and a histogram plotted (Fig. 5.6a). A slight minimum was found at 750-800m, but since rock wall amplitudes tend to be greater than 100m this does not seem a causitive factor. The data were not very satisfactory for this test since the maximum altitude in many grid squares is much lower than that at which rock walls occur nearby.

A better method of considering plateau altitudes is to plot all summit altitudes (defined by two closed contours of 10m intervals on the 1:50,000 O.S. map) as shown in Fig 5.6b. There is no evidence from this to suggest that the pattern of plateau summits is responsible for the gap in base altitude. Similarly, a plot of base and summit altitudes only shows one gap in summit altitudes related to the actual rock walls (Fig. 5.7). This occurs between 960m and 1010m, but the values in Table 5.1 indicate it is not related to the basal distribution.

Local variations in climate do not appear capable of causing the distribution of rock wall altitudes. Walls of both groups face in a variety of directions so that variations in solar heating, shading and snowdrifting would occur within both altitudinal groups rather than between them.

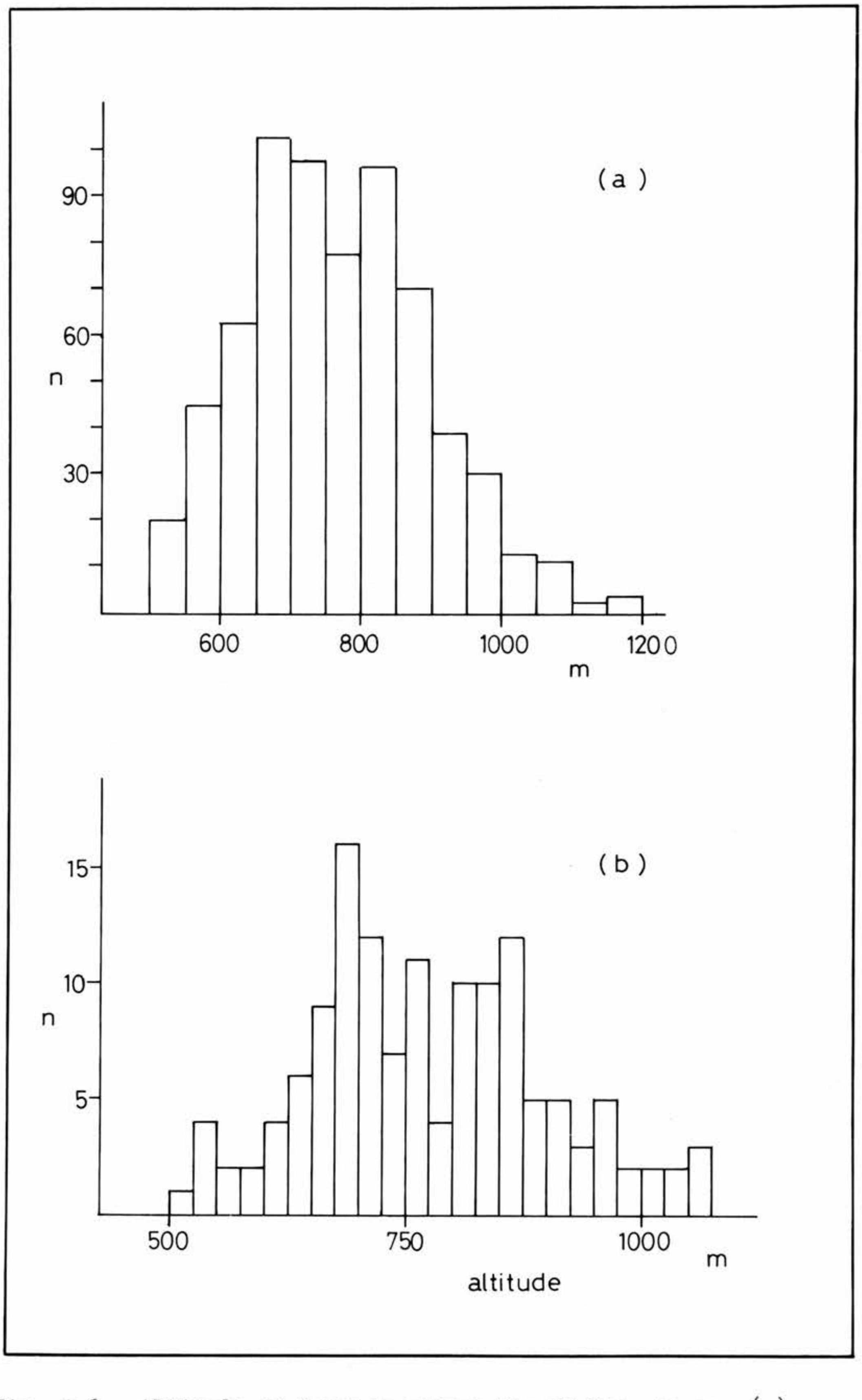


Fig. 5.6 Altitude of Summits across the SE Grampians: (a) maximum altitude within each grid square of 1km, (b) summit altitudes as defined in text

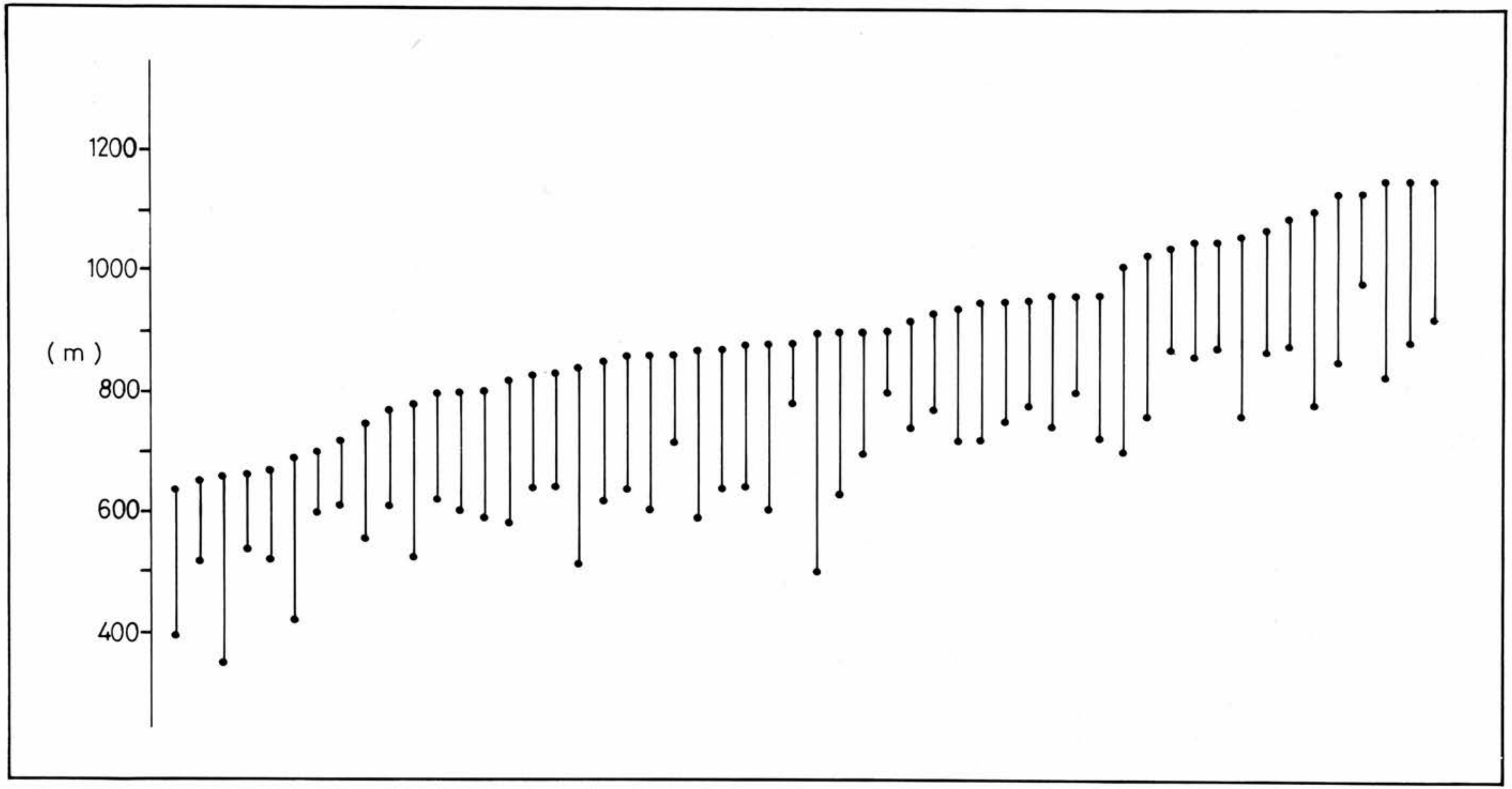


Fig. 5.7 Summit and Base Altitudes of Rock Walls in the SE Grampians

Fig. 5.5 indicates the remarkable similarity in rock wall base altitudes in some locations, as in neighbouring rock walls in Glen Clova, a valley at whose head there are three cirques, two of which have true rock walls. The valley has been heavily glaciated, its floor lying some 400m below the bases of the rock walls along its sides. The shapes and gradients of the valley head cirques indicate that ice has flowed over them from the plateau above (their back walls may be easily clambered up). The valley head rock walls have been subject to a different pattern and intensity of erosion and might be expected to occur at lower altitudes than those along their sides.

Rock walls along glaciated valleys in the SE Grampians east of Glenshee (to obviate regional variations) were divided into valley head and valley side or perched sites, and their base altitudes examined. Since some of these valleys do not have rock walls at their heads although they are cirques, they were included in the study, the altitude of the break of slope at the base of the headwall being used. The valleys considered were Glen Clova, Glen Callater, Glen Isla, Glen Prosen, Glen Esk, and Glen Muick. Little overall difference in altitude was found between the groups, the 'within group' variation being very high. The mean valley head base altitude is 578m $\pm$ 177m and that for perched sites 596m $\pm$ 119m. A Student's t test showed that the difference between the means was not significant at the 0.05 level (n_1=10, n_2=13, t=0.26). The valley side rock walls are only higher than the valley head rock walls in some cases. These findings suggest that the altitudes of rock walls in the area owe more to preglacial relief than to the efficacy of glacial erosion.

The Altitude of Rock Walls on Skye and Rhum

The rock wall altitudes of Skye and Rhum form a bi-modal distribution (Fig. 5.2b), with maxima at 400-450m and 600-650m. This distribution is not attributable to difference between the mountain groups since dispersion diagrams drawn separately for the Cuillins, and Rhum mountains, display bi-modal tendencies although that for the Eastern and Western Red Hills of Skye does not (Fig.5.8). In the Cuillins there is little relationship between rock wall base altitude and summit altitude since, as Fig 5.9 shows, the range of summit altitudes is very small. The map of the altitudinal and spatial distribution of rock walls in the Cuillins (Fig 5.10) shows that neighbouring rock walls (on the same or opposite sides of the Cuillin ridge) may vary widely in altitude. There is, therefore, no reason to suppose that the bi-modality is caused by orientation or locational variations.

The Cuillin ridge is apparently the only location in the study area where contiguous rock walls occur at distinct levels. Seven of the 28 rock walls occur between 607m and 649m and a further 13 between 470m and 535m. Only one wall lies between these heights. It is difficult to subscribe to Miller's (1961, 1975) proposal that cirque (or rock wall base) altitudes relate to fine adjustments or 'tuning' of glacial erosion to climatological conditions. The reconstruction of Loch Lomond Advance glaciers from geomorphological evidence (Sissons, 1977) indicates that glaciers occupied almost all the rock wall locations along the Cuillin ridge irrespective of previous base altitudes (which cannot have been very different from present). The estimated equilibrium firn lines of these glaciers ranged from 380m to 740m. Almost all of them lay below their respective rock wall base altitudes and varied with no discernible regard for them.

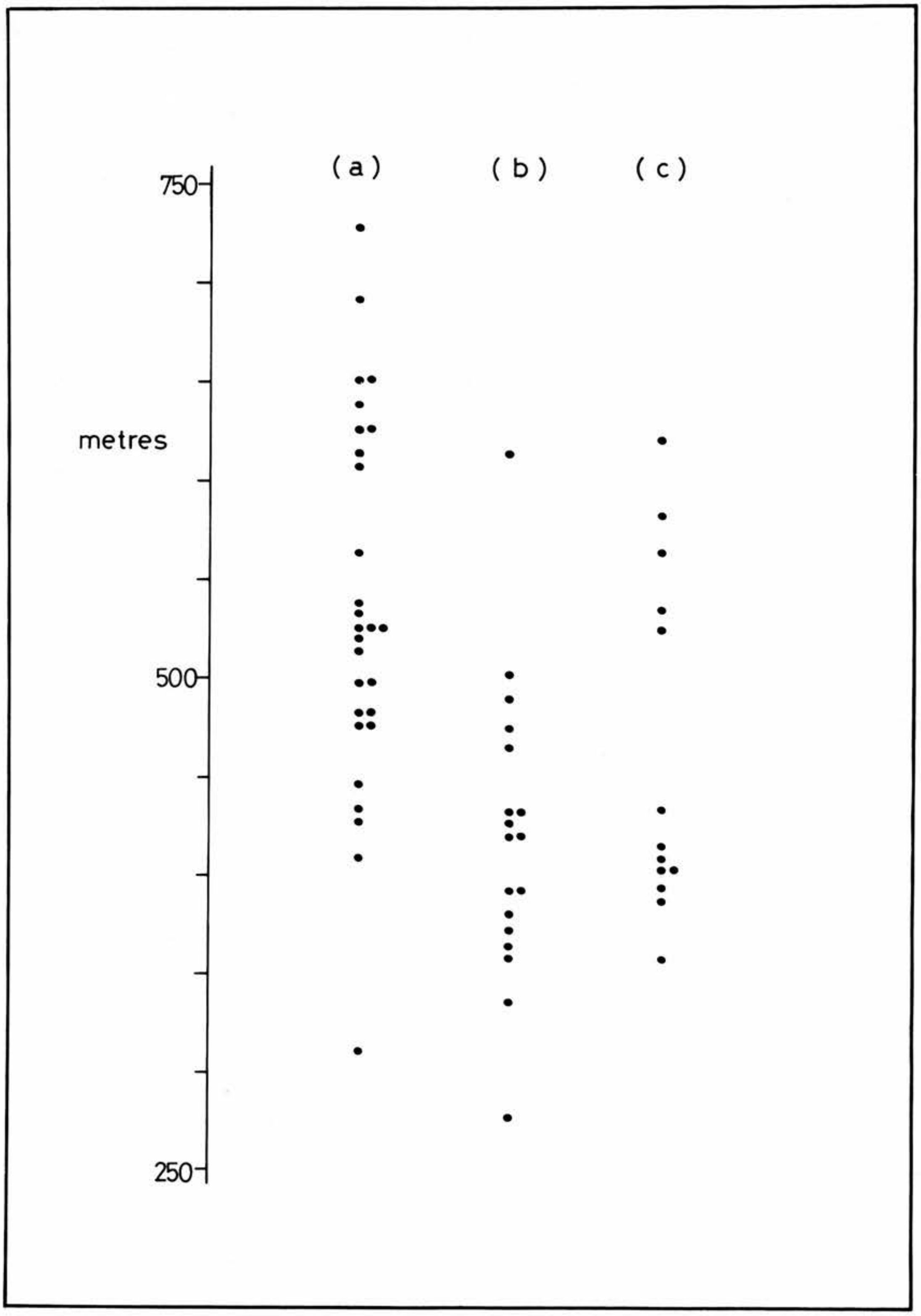


Fig. 5.8 Dispersion of Rock Wall Base Altitudes on Skye and Rhum: (a) Cuillins, Skye, (b) Red Hills, Skye, (c) Rhum

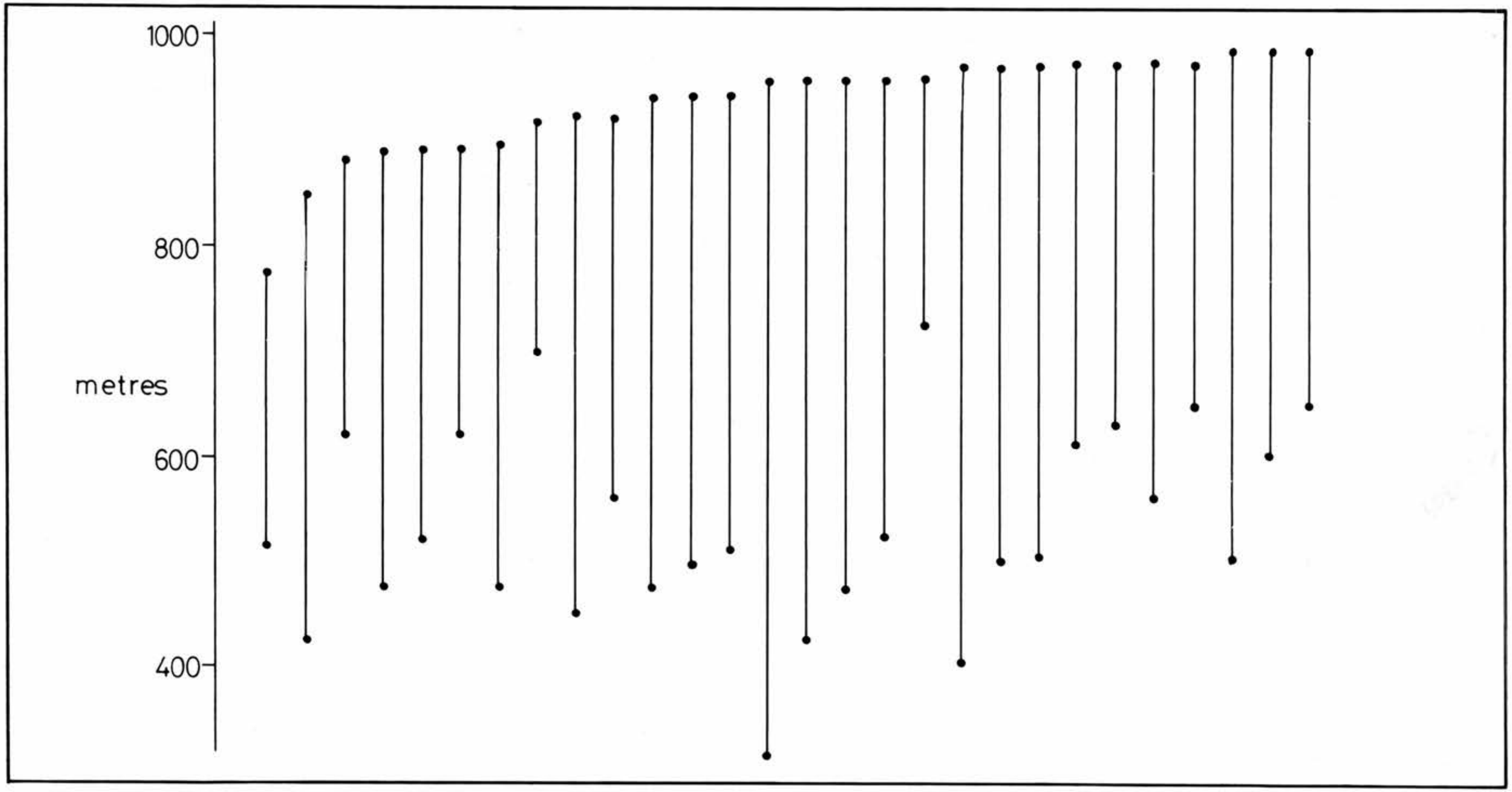


Fig. 5.9 Summit and Base Altitudes of Rock Walls in the Cuillins, Skye

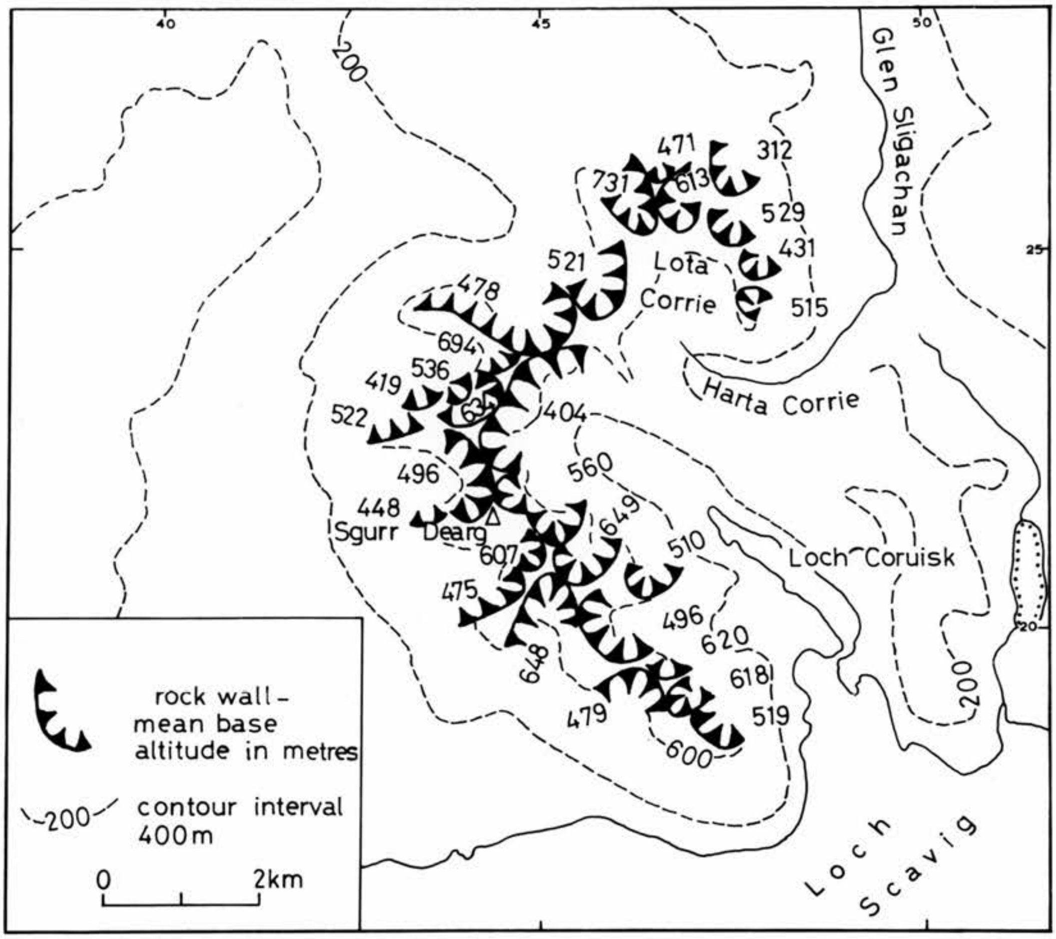


Fig. 5.10 Altitude and Location of Rock Walls in the Cuillins, Skye

The variation in altitude between the two rock wall groups is not geological. Although the igneous rocks of the Cuillins are layered (Hatch et al., 1961, p.493) the individual layers are not of sufficient thickness to produce the scale of altitudinal variations present.

The large number of rock walls between 470m and 535m indicates that rock wall altitudes are not randomly distributed. Rock walls are at low altitudes here compared with eastern mainland locations although summit altitudes are not correspondingly low. Since rock wall altitudes in the Cuillins are also insensitive to variations in orientation and windward/leeward slopes this area must have been extremely favourably situated for glacierization compared to other locations and several inferences may be made.

Firstly, accumulation of snow during the winter would have been high and with no slope benefitting from windblown snow, this was almost all directly due to precipitation. At such low altitudes this could only be achieved by moist air masses arriving from the relatively warm, neighbouring Atlantic and on being forced to rise sharply at the mountain barrier, depositing snow on both sides of the summit ridge.

The second inference that can be made is that the incipient glaciers would have been subject to relatively high ablation. Because of their proximity to the Atlantic Ocean, during the summer, the atmosphere would have been predominantly cloudy, air becoming saturated rapidly upon moving over the cold land surface. Evidence from the Loch Lomond Stadial suggests that mean July temperatures at sea level were well above freezing. Even at the altitude of the Cuillin rock walls precipitation would have fallen as rain for some part of the year, aiding ablation. At these low altitudes and close to the warmer ocean the ablation season was almost certainly longer than farther east and at higher elevations. It may therefore be inferred as in Chapter 3 that the range of precipitation across the study area was large, contrasts being particularly great between the high precipitation and high ablation of the most western mountains and the lower precipitation and lower ablation of the northeastern part of the study area where air had already been cooled and may frequently have begun to subside.

Because of the high mass balance of the Cuillin glaciers high erosion rates would also be expected. In addition, these rock wall glaciers were independent of external ice masses and hence erosion would have occurred unhindered for long periods. The altitudinal evidence supports the conclusions of the previous chapter and it is inferred that it was these factors occurring together that produced rock walls that have the greatest amplitudes in the field area.

The rock walls on Rhum also display a bi-modal distribution (Fig. 5.8). Five of the thirteen rock walls are evenly spaced between 516m and 615m, the rest being clustered between 355m and 430m. Although there is some relationship between summit altitude and rock wall base altitude, a Pearson's r correlation statistic of 0.34 was obtained between the two variables, which is not significant at the 0.05 level. Their occurrence at such low altitudes is consistent with the climatic inferences drawn from Skye.

Rock Wall Altitudes in the Monadhliath, West Highland and SW Grampian Regions

The rock walls in these regions have altitudinal populations that are normally distributed. In the SW Grampians the relationship between summit altitude and rock wall base altitude is indicated by rock walls occurring above 1000m in the Ben Nevis and Mamore Forest areas.

Many rock walls in the West Highlands occur at lower than average altitudes. Like Skye and Rhum, much of this area presents the first high land encountered by snow-bearing air masses and rock walls would be expected at low levels. However, rock walls are considerably higher on the mainland than on the islands. In previous chapters it was suggested that the large number of small rock walls in the West Highlands is due to the prevention of rock wall erosion by the coalescence of local and external ice and the submergence of rock wall source areas for long periods below a larger ice body. This may also explain the scarcity of rock walls at low altitudes where clearly the glaciation level was low. With rapid and massive net accumulation over the region suitable low altitude sites would have been overrun by westward moving ice streams early in any glacierization.

Rock walls in the Monadhliath Region occur close to the mountain summits (Table 5.1). This indicates that they are not just poorly developed in depth but also that the mountains are only just high enough for local glaciers to have formed during partial glaciations. During these periods, if this area was free of externally accumulated ice the altitude of the snowline was just below that of the mountain summits for only some time.

Summary and Conclusions

1. Rock wall base altitude is representative of the local or orographic snowline, generalised over many occupations of a site by glaciers responding to varying climatic regimes marginally suited to glaciation. Rock wall base altitude is therefore a useful indicator of the height of the equilibrium firn line in

many presently unglaciated areas that have been subject to partial glacierization.

2. Since rock wall altitudes are related to the glacierization period rather than to the equilibrium state the equilibrium firn line may have lain above or below the rock wall base altitude at any glacial maximum. The altitude of rock walls is likely to indicate the equilibrium altitude most closely where the rock wall ice sources have been independent of larger, external ice masses for long periods.

3. Rock walls vary widely in altitude across the study area, and vary in their position with respect to the mountain summits on which they occur (Table 5.1). The rock walls on Skye and Rhum tend to occur at the lowest altitudes and farthest below the mountain summits. The interior regions of the study area (the SW Grampians, Monadhliath and Cairngorm Regions) have rock walls at the highest altitudes.

4. Within regions rock walls are distributed at widely varying altitudes (Fig. 5.2). On Skye and Rhum, the SE Grampians and Cairngorms the local populations of rock walls are bi-modal while elsewhere distributions are uni-modal. Variations in short distances may be large and have been explained only to a limited degree. The bi-modal distribution in the Cairngorms may be related to pre-glacial erosion surface altitudes. In the more geologically complex SE Grampians no adequate relationship was found between summit elevations and rock wall altitudes, the area being notable for its remarkable altitudinal distribution of rock walls as well as for the similarity in rock wall altitudes over small areas. On Skye and Rhum, neither geological factors nor erosion surfaces satisfactorily explains the bi-modality of rock wall altitudes, these occurring irrespective of slope orientation or location. However, the occurrence of so many well-developed rock walls at

similar low altitudes here indicates a combination of high precipitation, high ablation and long periods when these features were eroded by independent glaciers developed in situ.

5. In contrast to these regions, the rest of the field area has uni-modal rock wall altitude distributions related to some extent to summit altitudes. This dichotomy may be due to the dynamic nature of glacierization. The regions that exhibit uni-modal rock wall altitude populations are the areas towards the centre of ice build-up during glacierization. These are therefore the areas in which most low altitude locations would have been glaciated by external ice before the local snowline had lowered sufficiently for local glacierization to take place. Hence the possibility of bi- or multi-modal populations (which may be the norm in many areas) is restricted and glaciers formed only in sites, suitable for glacier build-up early in the glacierization phase.

CHAPTER 6

REGIONAL VARIATIONS IN ROCK WALL ALTITUDES

Introduction

The last chapter was primarily concerned with local variations in rock wall base altitude. It was noted however, that in many studies cirque base altitudes have been integrated into regional patterns (e.g. Ljungner, 1949; Linton, 1959; Sale, 1970; Unwin, 1973). This chapter is therefore concerned with the regional trend in rock wall altitudes.

The Search for Regional Trends

Linton (1959) was first to demonstrate that the altitudes of cirque floors rise systematically across Scotland from west to east. He showed this graphically by placing a best-fit line by eye through each of four plots of cirque floor altitudes versus easting. Similar analysis was performed by Flint and Fidalgo (1964) who found a rise in cirque altitude from west to east in the Andes. These were informal uses of the regression method and pointed the way for similar but computationally more arduous methods that followed.

Dealing with a parameter that varies across a plane rather than along a line, such as cirque altitude, it is obviously desirable to represent the data as a best-fit surface rather than as a best-fit line. Porter (1964) accomplished this by drawing generalised contours by eye on a map of cirque floors in Alberta. This effort differed from normal contouring since it attempted to abstract the general trend across the area rather than follow the actual observed values. Thus the generalised contours were not placed through the actual data points but drawn smoothly across the surface so that the general trend was not obscured by random local detail.

With the advent of high speed computers in the late 1950's, complex mathematical and statistical procedures were constructed to analyse spatial data. The so-called objective methods of calculating best-fit three-dimensional surfaces, the group of techniques broadly known as trend surface analysis, were born.

Trend surface analysis is the statistical method most commonly encountered in the analysis of spatial data (Whitten, 1975). It has been applied most extensively by geologists and geophysicists, particularly in economic and mining geology. The early research and development was done in these disciplines (e.g. deLury, 1950; Oldam and Sutherland, 1955). Trend surface analysis was defined by Krumbein and Graybill (1965) as a

> '... procedure by which each map observation is divided into two or more parts: some associated with the 'large-scale' systematic changes that extend from one map edge to the other and the others associated with 'small-scale' apparently non-systematic fluctuations that are superimposed on the large scale patterns'.(p.321)

Although trend surface techniques assume that the sample data are subject to variation in several spatial scales, only two spatial scales are explicitly accounted for. These are firstly, a general widespread variation that may be represented by a mathematical function and secondly, local random variation that is incorporated in a measurement error term. In concept trend surface analysis is therefore very simple, the complex mathematical basis has been discussed in detail by many authors (e.g. Grant, 1957; Krumbein and Graybill, 1965; Unwin, 1975b).

In simple terms provided a variable (z) does not vary in an oscillatory manner a least squares 3-dimensional regression solution of a polynomial function of an a priori form may be fitted to the data (Unwin and Hepple, 1975), and may be expressed as

$$z_i = \Upsilon(U_i, V_i) + e_i \qquad (6.1)$$

where z_{ij} is the observed value of the dependent variable (in the present case rock wall base altitude) at location (U_i, V_j). $\Upsilon(U_i, V_j)$ is the trend component in the variation of altitude and e_{ij} is the local and error term, commonly called the residual.

To ensure that the least squares regression solution is the best unbiassed estimate of the population:

(i) the residuals must have an expected mean value of zero;
(ii) the residuals must be uncorrelated and have a constant variance;
(iii) there must be a greater number of observations than terms in the equations; and
(iv) the total population of residuals must have a normal distribution (Unwin, 1975b, p.20).

If these assumptions hold it is possible to use the trend surface results to make inferences about the total population and signifance testing may be carried out. A discussion of the general validity of the assumptions is given by Unwin (1975b).

The Application of Trend Surface Analysis to Rock Wall Altitudes

The least-squares regression solution (Equation 6.1) is only applicable to spatially continuous data. Using it in the analysis of rock wall altitudes it is convenient to think of the data as points of intersection between a continuous snowline surface and the surface topography (Unwin, 1973). Therefore the data represent a sample collected from a larger population.

For this regression design the data points must be evenly spaced over the whole study area. However, studies of former snowlines based on the location of independent glacier sources are bound to contain clustered data since the points of interest occur in clustered locations around mountain tops (Robinson, 1970). Several studies have shown that the trend result varies with the arrangement of the points (Harbaugh and Merriam, 1968, p.72; Doveton and Parsley, 1970) and may lead to a spuriously good fit (Norcliffe, 1969). Unwin (1975b) also suggested that distortions may occur if the mapped area is rectangular, and particularly at points close to the map edge. Clustered data pose serious problems in assigning degrees of freedom for significance testing.

Several methods may be used to overcome clustering. Norcliffe (1969) suggested that the plane in which the points are located could be changed, but this leads to later problems of interpretation. Sampling methods to obtain a more uniform spacing have been proposed by several authors. Harbaugh and Merriam, 1968, p.74) suggested removing some points in the closely spaced areas by placing a grid over the data map and randomly extracting only one point in each square. Robinson (1972) gave several sampling methods specifically designed for snowline data. As an alternative to randomly selecting one point from each grid square, he suggested a geographic sampling design, where one data point from each mountain group is selected. He produced trend surfaces using the raw data and the two evenly spaced distributions but was unable to find significant variations between the trends and hence doubted the importance of clustering. Gray (1972) was also unconvinced that clustering significantly altered results, but nonetheless favoured the use of a mean value based on geographic rather than grid areas.

In this study a grid mean design was chosen to reduce clustering. Trend surfaces based on an average value for each grid square of area $25km^2$ were constructed and used to explore and describe the trend in altitude within the data. Having transformed the rock wall data and computed the trend surface there are two problems: (i) to decide at what stage the polynomial expansion of Equation (6.1) is sufficient to define the trend and (ii) to assess both the geormorphic and statistical significance of that trend.

The objectives of the study are important in defining the trend, but the objectives that justify a trend surface approach are disputed. In his definitive paper Grant (1957) suggested that trend surface analysis is a satisfactory procedure whenever a generalisation of spatial data is required, while Chorley and Haggett (1965) considered that trend surfaces are response surfaces and thus must be used only for hypothesis testing. Unwin (1975b) supposed that trend surface analysis is valid in any situation from description to hypothesis testing of spatial data.

The arguments expressed by many authors concerning the suitability of the trend surface approach are often contradictory. Nonetheless, the method has much in common with other forms of regression analysis and provided the conditions applicable to a best-fit least squares solution are met the method may be used. The difficulty arises since these conditions are not often met with spatial data, and are certainly seldom so with data pertaining to discrete glacier source locations. However if the conditions of normality and non-correlation between the residuals are met the polynomial that best describes the trend may be chosen by significance testing (McIntyre, 1967). Two significance tests are possible, testing (i) the statistical significance of the proportion of the total sums of squares accounted for by all the terms in the function (e.g. Robinson et al., 1971), or (ii) the significance of the sums of squares accounted for by the next order in proportion to the residual sums of squares (Krumbein and Graybill, 1967; Chayes, 1970). The latter test is often made but may be unsatisfactory where the linear surface is not significant although higher order surfaces may be (Baird et al., 1971); this occurs if the trend surface is saddle or bowl shaped.

If significance testing is not possible then the trend cannot be defined on purely statistical grounds and unless an a priori hypothesis is being tested it is not possible to define and satisfactorily describe the trend. Grant noted this difficulty, and stated that the trend should be '... the simplest function whose residuals are trend-free' (Grant, 1957, p.325). If the trend surface is considered to be a response surface then its shape is known and Equation (6.1) may be expanded to contain the appropriate number of inflexions. Norcliffe (1969) indicated that in the physical sciences hypotheses are rarely highly complicated and that trends confined to linear and quadratic terms are likely to be satisfactory. The quintic surface describing cirque moraine altitude derived by Unwin (1975a), for example, is impossible to interpret geomorphologically.

In this study there were two objectives in using trend analysis. Firstly, the technique was employed as a search tool in order to describe large scale systematic variations in rock wall base altitude. Secondly, the technique was used to test a strictly formulated hypothesis, residual maps being produced in each case. The SYMAP computer package (Schmidt and Zafft, 1975; Webster, 1979) was employed to carry out the computations since it is a widely used mapping package implemented by the local computing centre.

The Regional Pattern of Rock Wall Altitudes

An initial run of the package with all the data points indicated that the population is very highly clustered. A first order nearest neighbour statistic (Clarke and Evans, 1954) of 0.37 was obtained, showing that the data were not suitably spaced for trend analysis to proceed. In order to explore the altitudinal pattern further a $25km^2$ grid of 126 points was constructed from all mainland rock walls. This produced a randomly spaced pattern, the first order nearest neighbour statistic being 0.96. The trend surfaces constructed for the first two orders are reproduced in Fig. 6.1 and the associated informal analysis of variance is given in Table 6.1. The quadratic surface explains 38% of the variation in rock wall altitude, the variance test showing that the cubic surface does not add significantly to this. The residuals from the quadratic surface are not greatly autocorrelated and thus this surface satisfies Grant's (1957) guidelines. The quadratic surface rises inland from the western edge of the study area, the maximum altitude being reached in the north over the eastern West Highland Region and the Cairngorms. The surface falls to the SE over the SE Grampians.

The shape of this surface varies markedly from the best-fit surface of cirque floor altitudes constructed by Robinson et al., (1971), their surface being best described as a ridge with an axis that runs SW-NE over the present study area and rises northeastwards. Their surface was constructed from highly clustered data (a nearest neighbour statistic of 0.41).

The use of gridded data means that the variance in data values where they are closely spaced is reduced compared with areas where rock walls are widely scattered. However, this method of reducing clustering was preferred over that which randomly selects one wall to represent the grid square (e.g.

Fig. 6.1 Linear and Quadratic Trend Surfaces of Gridded Rock Wall Altitude Data

Table 6.1 Informal Analysis of Variance
Trend Surfaces of Gridded Data: Base Altitude

	SS	d.f.	F.ratio	p
Linear	253613	2	0.60	> 0.05
Deviation from linear	2598547	123		
Plus quadratic	830674	3	16.53	< 0.001
Deviation	1767873	120		
Plus cubic	142193	4	2.54	< 0.05
Deviation	1625392	116		

Harbaugh and Merriam, 1968) since, as shown in Chapter 5, neighbouring rock walls in some instances vary widely in altitude.

Having found that spatial trends do exist in the rock wall altitude data, and that location accounts for a significant proportion of the variance, the trend surface technique was employed for hypothesis testing. In Chapter 3 a model of precipitation distribution over much of the British Isles during glacierization was proposed following a discussion of the distribution of rock walls in the study area and backed up by evidence form several fields. It was considered that during rapid glacierization such as during the Loch Lomond Advance, precipitation was not very different from the present in western areas, but that it was diminished in the east. With the boundary between subtropical and polar waters becoming sharper (Ruddiman and Glover, 1975) and migrating southwards (Ruddiman and McIntyre, 1976) to the latitude of the British Isles at the onset of glacierization, two things are likely. Firstly, a more vigorous atmospheric circulation resulting in frequent cyclonic depressions would occur and secondly, many depressions would be swept across Scotland embedded in west to southwesterly airstreams. The accompanying winds would veer from east of south before the warm front and to SW-west following it. The combination of contrasting temperatures between the cold land surface and the warmer ocean, and the orographic effects of the western mountains ensured high precipitation in this area but a drier, and, in the lowest layers colder, descending air mass farther east. The differences between west and east would have been further accentuated since continental airstreams that at present provide the Eastern Highlands with a high proportion of their winter snowfall would have been much drier being unable to absorb moisture on their passage over a frozen North Sea (at least in winter).

Discussion in Chapter 5 indicated that regional variations in rock wall base altitudes are closely related to the average altitude of glacierization provided local variables are eliminated. The rock wall base altitude expresses the altitude (during partial glaciation or at the onset of full glacial conditions) at which accumulation over many winters is equal to the loss of snow and ice during the ablation season. While ablation rates are largely a local variable, depending on aspect and altitude of the rock wall, accumulation, particularly in terms of precipitation varies regionally. The quantity of snowfall received depends on the position of the rock wall with respect to regional mountain barriers, and distance from the moisture source. As part of the general theory of rock wall locations it is proposed that systematic regional variations in rock wall altitudes are largely the result of altitudinal adjustments to variations in winter snowfall across the field area. It is hypothesised that the regional trend of rock wall altitudes is thus a response to the above pattern of precipitation across the study area during glacierization.

The hypothesis was tested by defining the trend of rock wall base altitudes using trend surface analysis. Specifically, it was hypothesised that the trend rises steeply eastwards from the west coast and also rises NE from the SW Grampians and NW from the Highland Boundary. It was envisaged that such a trend would consist of two inflexions at most, and therefore cubic trends were the most complicated surfaces computed. Several trend surface designs were used in this analysis. To reduce clustering the field area was divided into sections, thus obviating the problem of lowland areas between mountain groups (Webster, 1979). This also meant that areas were defined by edges varying less in length than those of Fig. 6.1.

The whole field area was divided into strips, the first composed of all rock walls east of easting 2825, an area of plateaux comprising the SE Grampians and Cairngorms. The resulting nearest neighbour statistic for 100 rock walls is 0.66, which represents a slightly clustered distribution. Table 6.2 shows the related informal analysis of variance. This analysis was done since the evidence of Robinson (1970) and Gray (1972) suggests the technique is robust enough to overcome some clustering. The cubic surface (Fig. 6.2) increases the degree of explanation over the quadratic plus linear surface by a significant amount and explains 61.6% of the variance. This surface rises to a centre over the eastern Cairngorms and also rises towards the western part of the SW border of the map. The variation in trend altitude is from 480m in the extreme east in the SE Grampians to 965m in the central Cairngorms.

It was felt desirable however, to eliminate local altitude variations where possible and so trend analysis was carried out over the same area using only the rock walls facing between north and east (c.f. Porter, 1964). This yielded a less clustered trend best described by a quadratic expansion that explained 57.7% of the variation (Table 6.3). In much of the

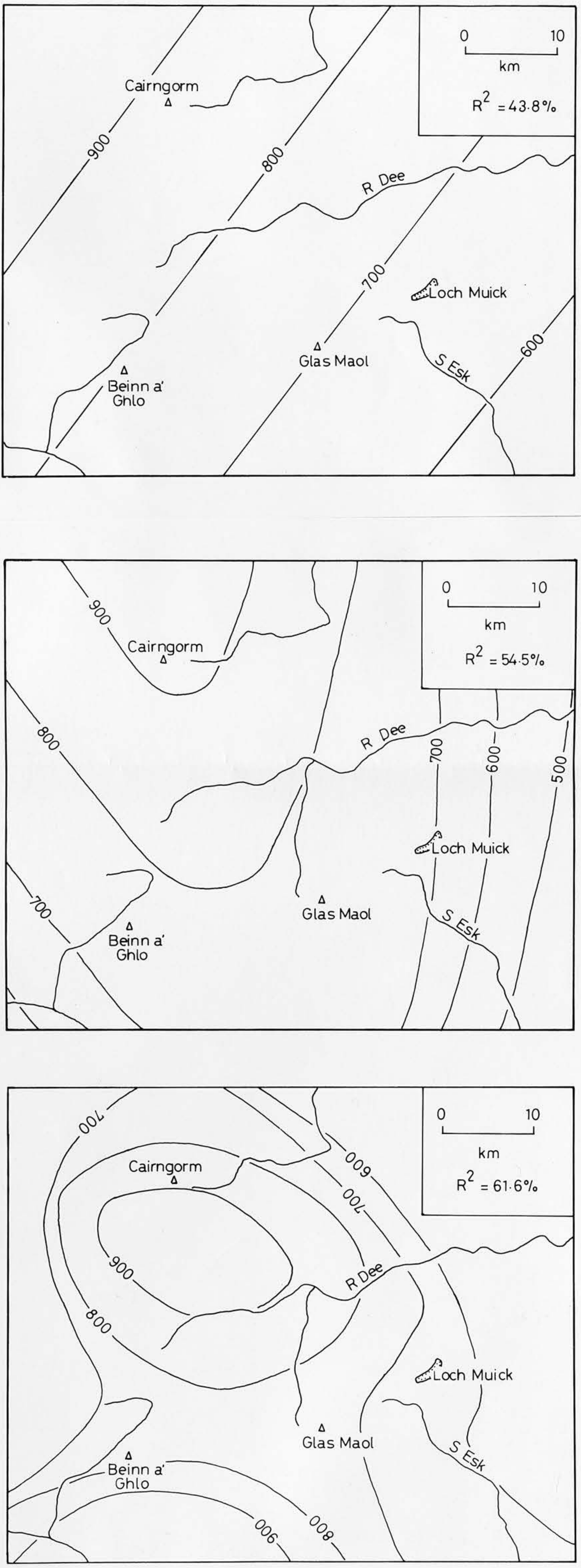


Fig. 6.2 Trend Surfaces of all Rock Wall Altitudes in the SE Grampians

Table 6.2 Analysis of Variance for Trend Surface of all Rock Wall Base Altitudes east of 2825

	SS	d.f.	F-ratio	p
Linear	1284025	2	37.78	< 0.001
Deviation from linear	1647895	97		
Plus quadratic	304926	3	7.16	< 0.001
Deviation from quadratic	1332969	94		
Plus cubic	206859	4	4.13	< 0.01
Deviation from cubic	1126110	90		

map area the quadratic trend surface is lower in altitude than that for all data points, thus indicating some relationship between rock wall aspect and altitude (Fig. 6.3). This surface rises steeply northwestwards from below 400m in the SE Grampians towards the Cairngorms where it is above 900m. The surface falls less steeply southwestwards again from the Cairngorms. The effect of aspect on rock wall altitude is examined more rigorously in Chapter 8.

Table 6.3 Analysis of Variance for Trend Surface of N,NE and E-facing Rock Wall Base Altitudes, east of 2825

	SS	d.f	F-ratio	p
Linear	954264	2	28.78	< 0.001
Deviation from linear	1152296	70		
Plus quadratic	260878	3	6.54	< 0.01
Deviation from quadratic	891417	67		
Plus cubic	44799	4	0.8334	> 0.05
Deviation from cubic	846618	63		

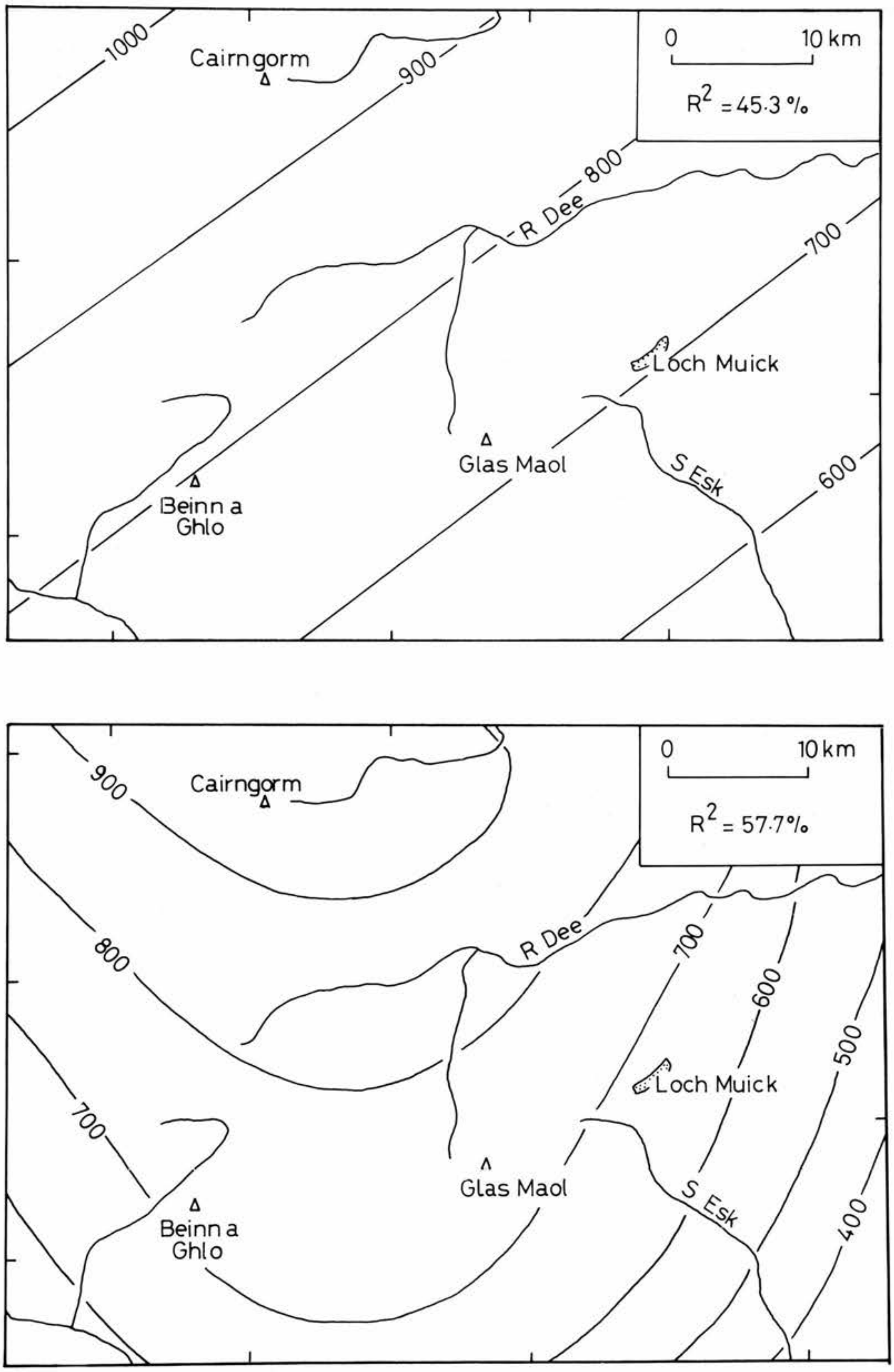


Fig. 6.3 Linear and Quadratic Trend Surfaces of N-, NE-, and E-facing Rock Walls, SE Grampians and Cairngorms

Similar trend surfaces were calculated for two more strips. These areas were defined so that the first contains the rock walls in the Monadhliath Region, the SW Grampians and those of Glen Garry while the latter is composed of all former rock walls on the mainland west of the Great Glen and some of those in the SW Grampians (Figs 6.4, 6.5).

In the global analysis (Fig. 6.1) the central part of the field area was represented by the central portion of a saddle rising from the west and falling generally towards the east but which is high in both the north and south of the field area. Analysis of the 113 rock walls in the central strip (Fig. 6.4) facing between north and east yielded a linear trend surface that explained only 11.1% of the variation in the sums of squares. Informal analysis of variance may not be an appropriate tool for measuring significance here since the data are highly clustered. Howarth (1967) suggested how to overcome this problem following experiments on random data. He found that 95% of the observed values of the %RSS were smaller than 6.0,12.0 and 16.2% for linear, quadratic and cubic surfaces respectively. He suggested these values be taken as the upper end of chance occurrence by random data. On this basis the linear surface is significant at the 0.05 level. The inclusion of quadratic terms increase the %RSS to 32.8. This result is in sympathy with the reservations of Baird et al. (1970) since here is an instance where the significance of the surface fit increases with an inflexion rather than decreases. The cubic surface, however, is not significant even at the 0.05 level. The trend is shown in Fig. 6.4 and the analysis of variance in Table 6.4. The highest data point trend value on the quadratic surface is 834m in the Ben Nevis range and the lowest is 507m in the NW. These are 33m and 62m above and below the observed values respectively.

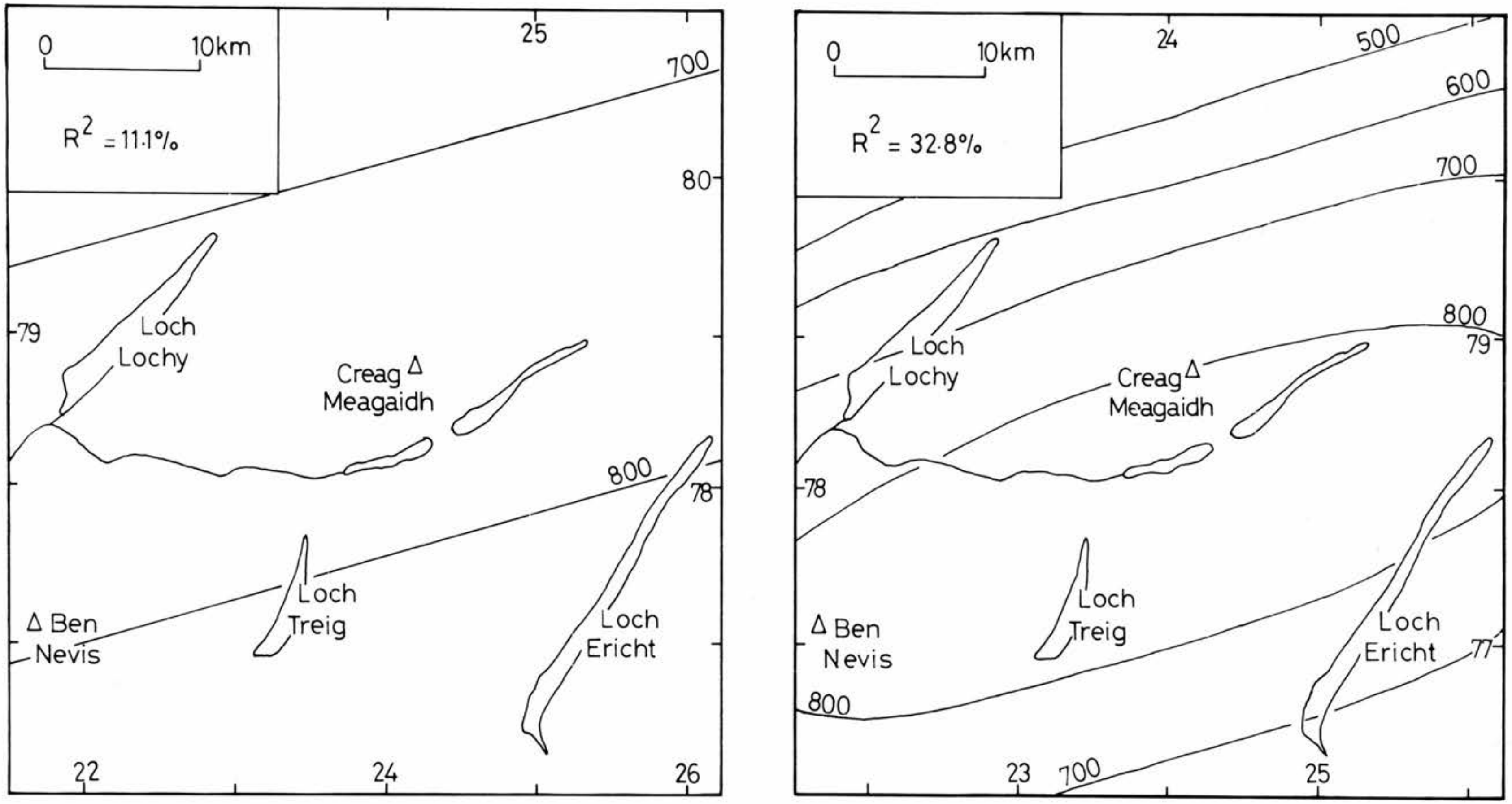


Fig. 6.4 Linear and Quadratic Trend Surfaces of N-, NE-, and E-facing Rock Wall Base Altitudes, Eastings 2150 - 2625

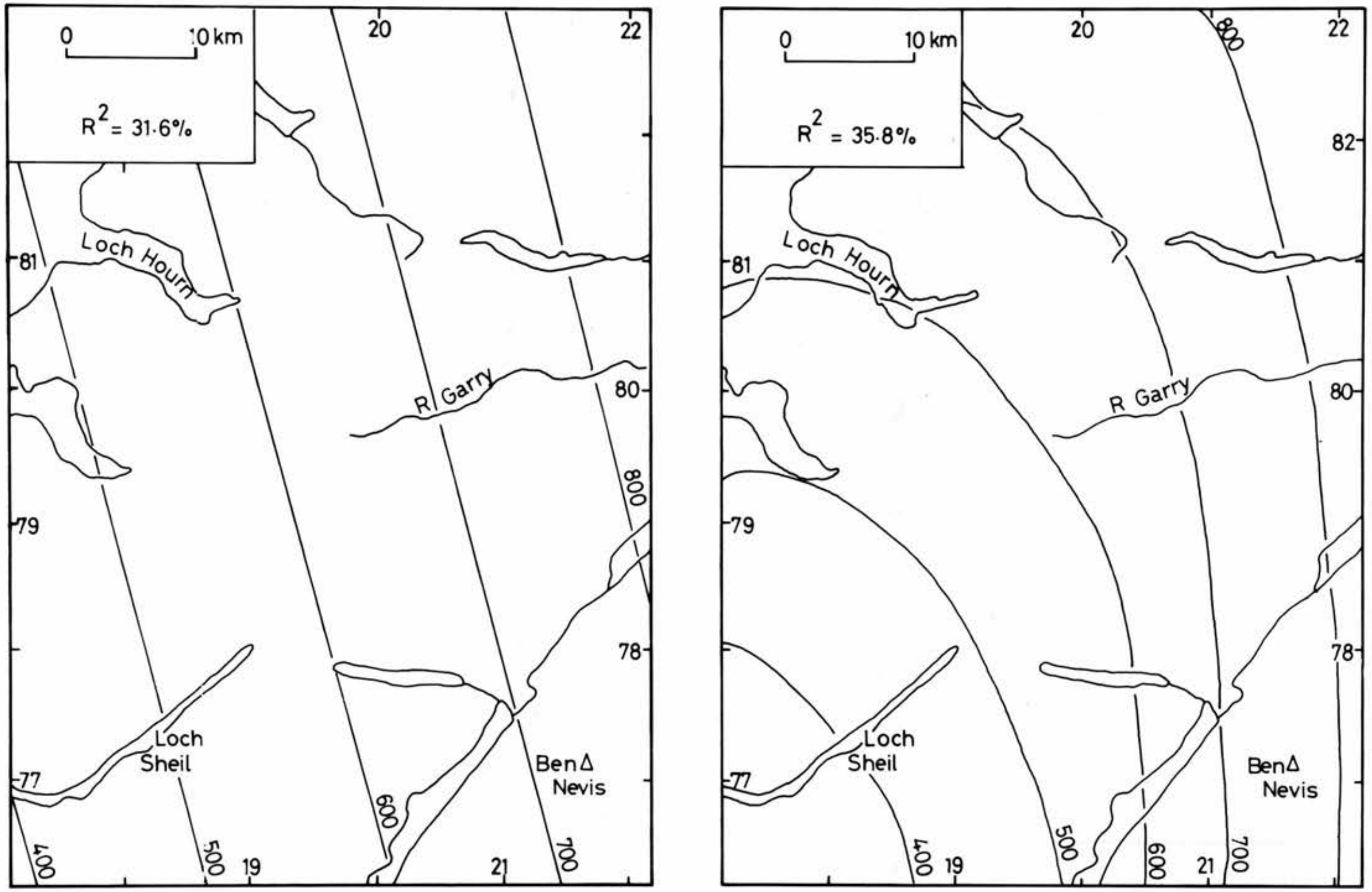


Fig. 6.5 Linear and Quadratic Trend Surfaces of N-, NE-, and E-facing Rock Wall Base Altitudes West of 2200

Table 6.4 Analysis of Variance for Trend Surface Analysis of N-, NE- and E-facing Rock Wall Base Altitude lying between Easting 2150 and 2625

	SS	d.f.	F-ratio	p
Linear	171891	2	6.90	< 0.01
Deviation from linear	1370749	110		
Plus quadratic	334513	3	11.51	< 0.001
Deviation from quadratic	1036236	107		
Plus cubic	74506	4	1.99	> 0.05
Deviation from cubic	961730	103		

The global trend surface (Fig. 6.1) shows a trend rising across the West Highlands from the coast, with isolines concave to the coastline. A trend surface was carried out on the rock walls with favourable aspects west of easting 2200. All aspects between NW and east were used since many rock walls in this region face slightly west of north. The 155 rock walls are fairly highly clustered giving a nearest neighbour statistic of 0.54. Informal analysis of variance (Table 6.5) shows that the quadratic surface is appropriate, explaining 35.8% of all the variation in the sums of squares. The quadratic equation describes a surface rising to the NE and east from a minimum data point trend value of 413m to a maximum of 834m.

Table 6.5 Analysis of Variance for Trend Surface of N-,NE- and E-facing Rock Wall Base Altitudes west of 2200

	SS	d.f.	F-ratio	p
Linear	1236517	2	35.6	< 0.001
Deviation from linear	2671387	154		
Plus quadratic	163447	3	3.3	< 0.05
Deviation from quadratic	2507940	152		

If rock wall altitude is mainly an inverse function of snowfall, the trend surfaces shown in Figs 6.3-6.5 do resemble the pattern of precipitation envisaged above: those areas where precipitation was expected to be high coincide with areas of low trend surface altitude. Rock wall altitudes follow a rising trend inland from the west coast, the systematic increase in altitude indicating the level at which declining precipitation (at any altitude) equals ablation (regionally similar for any altitude). However, superimposed on this hypothesised trend is a northerly rising component particularly across the SE Grampians and the Cairngorms, and a southerly rising component over the Ben Nevis and Mamore Forest ranges.

Variations between the Precipitation Model and the Trend Surface

The trend surfaces may initially appear to be response surfaces to the distribution of summit altitude and therefore orographically induced precipitation rather than the regional precipitation gradient, since they are high over both the Cairngorms and SW Grampians and lower towards the Highland Boundary. Two factors suggest that this is not the case. Firstly, if rock wall altitudes were only a response to orographic precipitation, rock walls on mountains with the same summit altitude any where in the study area would occur at similar altitudes, the 'trend' surface thus being horizontal. Instead, statistically, rock walls in the Cairngorms are likely to occur at higher altitudes than elsewhere indicating that at any altitude precipitation was lower here.

Secondly, regression analyses of summit altitudes and rock wall base altitudes were carried out for the Cairngorms and SW Grampians and showed distinct directional and gradient trends. A multiple stepwise regression design (Miesch and Connor, 1968) was employed since summit altitudes increase only marginally

($p < 0.1$) with easting. The trend in summit altitudes rises steeply northwards whereas that for rock walls rises northwestwards (Fig. 6.6). There is much more high ground in the northern part of the West Highland Region than in the southern part yet the quadratic trend surface rises eastwards and northeastwards rather than northwards.

Despite this there is a tendency for rock walls around individual high summits to occur at altitudes above the regional trend. This is understandable if the glacierization process is viewed dynamically. As the altitude at which glacierization is possible is lowered, sites just below the highest summits may be occupied while sites on neighbouring lower summits are below the glacierization level.

The trend surfaces of rock wall altitude do not exactly represent the precipitation pattern during partial glaciation because of the dynamic nature of glacierization itself: an implicit assumption in the use of trend surface analysis for hypothesis testing is that rock wall erosion across the field area was contemporaneous and that the rock walls responded to just one precipitation pattern. However, some peripheral rock walls at low levels may have been eroded in response to a set of climatic conditions which, in areas of higher precipitation, had already caused the rock wall glaciers to be enveloped by valley and piedmont ice streams. While the lower peripheral sites were being eroded and enlarged by local glaciers, rock walls most favourable to glacierization were being eroded and possibly degraded by larger ice bodies.

Nonetheless, the trend surfaces closely follow the general pattern indicated by the hypothesised precipitation model. Although discrepanies are inevitable because of the influence of topography and the dynamic aspects of glacierization, the marked rise in the trend surface nortwestwards from the Highland Edge

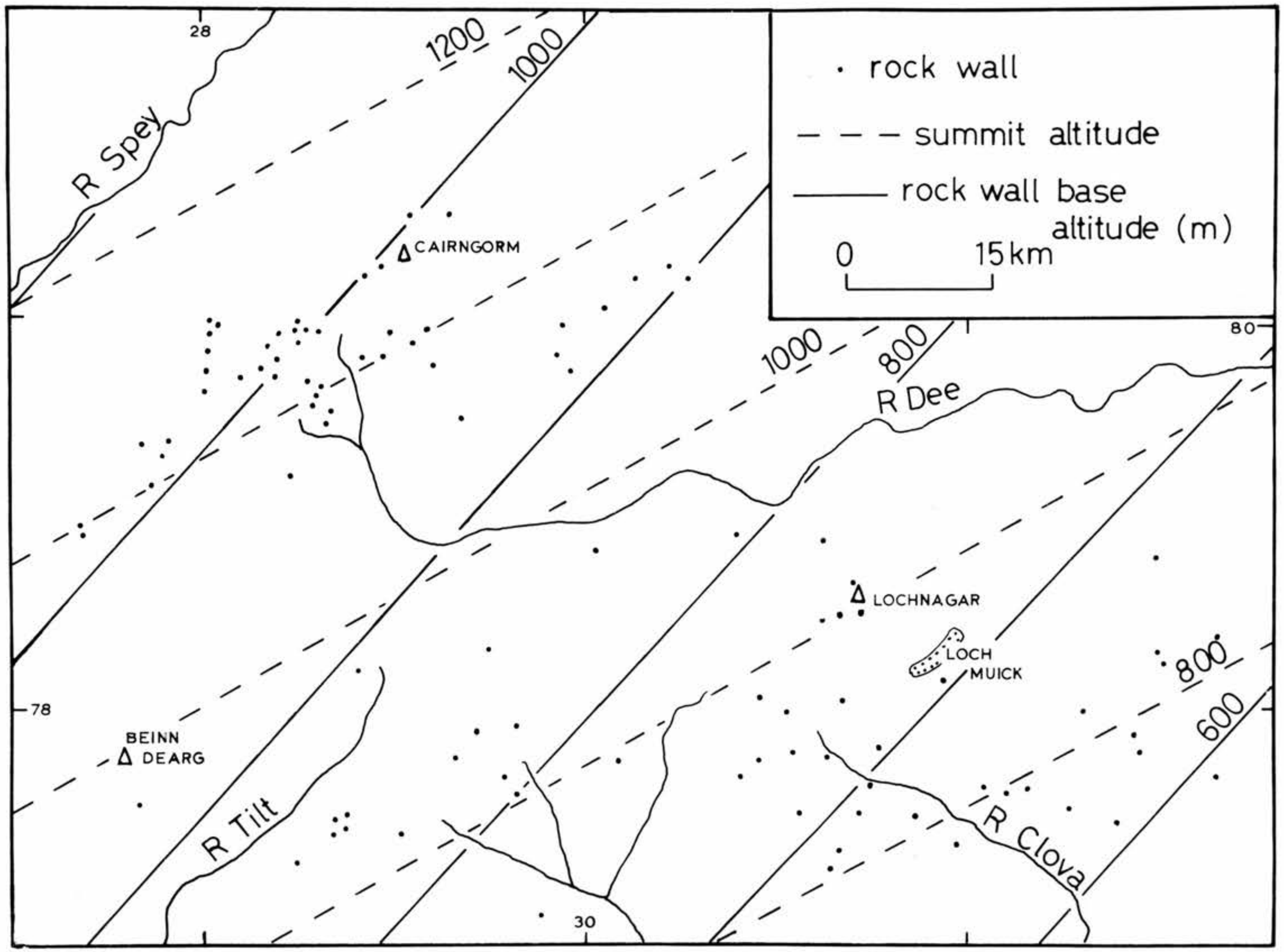


Fig. 6.6 Comparison of Trends in Summit and Base Altitudes across the SE Grampians and Cairngorms

was not expected. It is interpreted as a decrease in solid precipitation in that direction so that at any altitude there was less accumulation and, in an environment only marginally suited to glaciation, a positive mass balance would have occurred only at higher altitudes. This interpretation is consistent with independent evidence from the Loch Lomond Advance. Sissons (1974a, 1979b) found evidence of an ice cap over the Gaick plateau and one over the SE Grampian plateau at 800m and south-facing cirque glaciers at the Highland Edge at 600m, whereas glaciers only occurred at high levels in the Cairngorms in sites protected from insolation and favoured for wind-blown snow accumulation. Palynological studies carried out in the Spey valley (Birks and Mathewes, 1978) indicated that at low altitudes, during the Loch Lomond Stadial, this area was relatively starved of precipitation.

The model of precipitation distribution must therefore be modified to take into account the increase in altitude of rock walls across the SE Grampians and Cairngorms. During periods of partial glaciation, not only was there a decrease in precipitation at any altitude away from the west coast but also a decrease northwestwards from the Highland Edge.

Synoptic Inference from the Trend in Rock Wall Altitudes

The trend surfaces drawn from rock wall altitudes may be used to infer the average regional spatial pattern of precipitation prevalent during periods of rock wall erosion and may be used to infer typical winter synoptic weather patterns during periods of partial glaciation and the initiation of full glacial conditions.

The presence of a sharply defined oceanic polar front migrating southwards past the British Isles at the onset of glacial conditions means that most atmospheric depressions were concentrated in a track much narrower than at present and with vigorous atmospheric circulation land areas at the latitude of the migrating front experienced a constant stream of depressions. The trend surface rising eastwards from the west coast is consistent with depressions tracking from the west. However, the northwestward trend across the SE Grampians suggests that snowbearing winds gave greater snowfall at the Highland Boundary than in the interior of the SE Grampians, and so during periods of snowfall air movement was frequently SE-NW or south-north. This situation is most likely to have occurred with depression centres passing across the southern British Isles. A decrease in precipitation across the area is also likely to have occurred during non-frontal snowfall due to the forced uplift of unstable air travelling north or NW across the Highland Boundary. As an air mass is dried by orographic precipitation, so it requires greater uplift to procure the same accumulation of snow. Thus for any altitude, precipitation would have decreased in a north to northwesterly direction from the Highland Edge.

The typical winter synoptic situation during glacierization may be one of a constant series of depressions tracking eastwards across the British Isles. Winds circulating around such depressions would be southeasterly to southerly before the warm or occluded front, veering to a more westerly direction following the passage of the occluded or cold front. As the polar front in the Atlantic migrated beyond the latitude of the British Isles the study area would have become less affected by the associated depressions.

During the summer the distribution of precipitation would have been different. For example, Coope (1977) inferred from the coleopteran evidence that during the Loch Lomond Stadial the mean July temperature was a little below $10^{o}C$ in the

Midlands. Sissons (1979a) inferred a mean July sea-level temperature of 6°C in the SE Grampians. This means that in summer much precipitation fell as rain rather than snow and so aided net ablation rather than accumulation. This would have been most effective close to the west coast since there the air masses would have been warmest. As the lowest layers of the atmosphere were cooled by passage over the cold land surface, the likelihood of summer snow would have increased, being particularly so at the higher rock wall altitudes of the NE of the study area. Hence through late spring and autumn especially, while rainfall aided ablation at low-lying westerly rock walls the walls of the Monadhliath Mts and the Cairngorms may have experience additional snowfall. Tronov (1962) indicated the importance of late spring and summer snowfall in inhibiting ablation. It is therefore suggested that variations in winter snowfall across the study area were very great during periods of glacial accumulation.

Conclusions

1. Systematic variations in rock wall base altitude over a small latitudinal range generally relate to systematic variations in precipitation. With increasing distance from the moisture source higher altitudes must be sought to obtain the equivalent preicipitation.

2. Trend surface analysis was chosen as the most appropriate method presently available for testing a proposed model of precipitation distribution during periods of glacierization despite its methodological drawbacks. To avoid problems of clustering and autocorrelation trend analysis was used to test a hypothesis with a definite number of inflexions. It is suggested that this is the most appropriate method of using the technique when data such as rock wall locations are being analysed.

3. The trend surfaces correspond quite closely to the proposed model of precipitation. However, the model was altered to account for the rapid rise in altitude of rock walls northwestwards from the Highland Edge. This is inferred to be the result of forced uplift and consequent precipitation through unstable air masses at the topographic boundary as well as enhanced uplift at warm or occluded fronts with associated SE-southerly winds.

4. From trend surfaces of rock walls average synoptic climatic conditions during glacierization may be inferred. The trend surfaces suggest that precipitation varied widely across the field area during the winter accumulation season due to very frequent depressions moving eastward across the area with south to SE winds accompanying the associated warm or occluded fronts. The interaction of these with the land surface topography gave largest precipitation totals in the western Highlands and to some extent along the Highland Boundary. This would have been most effective if winter depression centres were located close to the latitude of the field area. When the sharp oceanic thermal boundary was pushed far south of the study area latitude, as at the Late-Devensian maximum (Ruddiman et al, 1977), the driest parts of the field area must have had very little precipitation.

CHAPTER 7

THE AZIMUTHAL DISTRIBUTION OF ROCK WALLS

Introduction

Cirques in a given area tend to display a preferred orientation that is closely related to the preferred orientation of small glaciers (Evans, 1977). This characteristic has been used as evidence for their glacial origin (e.g. Helland, 1877). The reasons for a preferred orientation have largely been sought in terms of the climate operating during their formation and, this being so, the actual patterns displayed have been utilised in reconstructions of palaeoclimates.

In this chapter methods of displaying and statistically analysing the azimuthal data collected in cirque and rock wall studies are discussed, and a statistical test new to this application is introduced. The azimuthal distribution of former glacier source walls in the whole study area is then presented and discussed, followed by the display of the relationship between rock wall altitude and azimuth in each of the regions of the field area. The distribution across the study is compared and contrasted with the distribution of cirque aspect found by other workers on Scottish cirques and in the rest of Western Europe. A discussion of the influence of climatic parameters is preceded by the consideration of the contribution made by non-climatic factors to the distribution of rock wall and cirque aspects. Finally this discussion is expanded in terms of the various distributions of rock walls azimuths found in different parts of the study area, and palaeoclimatic inferences are made.

The term asymmetric distribution is now in common usage to mean a distribution of cirques that displays a preferred orientation. The term is avoided in this thesis since this use of asymmetric is not the normal mathematical sense of the word. In the present work the term clustering is preferred to asymmetry. Orientation vector directions are given throughout in degrees, from 0^{o} to 360^{o}.

The Display and Analysis of Orientation Data

The azimuthal distribution of former glacier source walls may be displayed in several ways. As a preliminary, rose diagrams and polar-altitude diagrams are normally drawn (e.g. Seddon, 1957; Andrews et al., 1970; Clough, 1977). Evans (1974, 1977) has also introduced the use of the cumulative vector as a form of display. This is closely connected with vector analysis and its statistical properties are discussed below. The cumulative vector differs from the other forms of data display since it purports to show the resultant vector of an aggregation of all the individual azimuths. The cumulative vector is thus useful not only in displaying data but also as a measure of central tendency.

The use of statistics in the analysis of orientation data presents problems if linear methods are used since the data must be 'flattened out' by cutting the circle at some arbitrary point. As Curray (1956) pointed out the resultant mean and variance are dependent on the choice of origin. A more appropriate measure of central tendency in a circular distribution is the vector mean. Pincus (1956) defined this as the azimuth for which resultant vector strength is maximised. Curray (1956) presented a method of calculating the vector mean by a summation of the north-south and east-west components of individual orientation measurements using the formula

$$\bar{\Theta} = \tan^{-1}\left(\sum_{i=1}^{n}\sin\Theta_i / \sum_{i=1}^{n}\cos\Theta_i\right) , \qquad (7.1)$$

where n is the number of data points for which orientations Θ_i lying between 0^o and 360^o have been observed. The mean vector direction $\bar{\Theta}$ is a measure of central tendency that is independent of origin. Two further results may be obtained:

$$R^2 = \left(\sum_{i=1}^{n} \sin\Theta_i\right)^2 + \left(\sum_{i=1}^{n} \cos\Theta_i\right)^2 \qquad (7.2)$$

$$L = (R/N).100\% \qquad (7.3)$$

R represents the magnitude of the resultant vector and L is the vector strength: as such L is a measure of dispersion about the vector mean.

Curray (1956) gave three methods of testing for the significance of two-dimensional orientation distributions against randomness or uniformity that are now in common geological and geomorphological usage. They are the chi-square test (e.g. Andrews, 1963), analysis of variance (e.g. Griffith and Rosenfeld, 1953) and the Rayleigh test (Rayleigh, 1919; Evans, 1974).

The chi-square test is a non-parametric statistic used to test for significant departures from a uniform distribution of points about a circle (Batschelet, 1965, p.25). It is simple to calculate and is appropriate for analysis of circular distributions with a single dominant mode. It gives no information on the distribution of orientation values however (Pincus, 1953), and significant results do not necessarily represent a preferred orientation (Curray, 1956). Ballantyne and Cornish (1979) showed that the chi-square value obtained varies with the choice of sectors into which the measurements are grouped and suggested that other tests are more appropriate.

The F-ratio test proposed by Griffith and Rosenfeld (1953) has been evaluated by Curray (1956) and Evans (1974, p.181). This test is not particularly suitable for orientation data since it requires calculation of the minimum variance which corresponds with a mean, calculated by cutting the circular data at the minimum point, rather than using the more suited vector mean and strength. Evans also concluded that the F-test underestimated deviations from randomness.

The Rayleigh test (Rayleigh, 1894, pp.35-42) is based on vector strength and was adapted to suit geological data by Curray (1956) with the formula

$$p = e^{(-L^2 n)(10^{-4})} \quad , \qquad (7.4)$$

where p is the probability of obtaining a greater value by chance, n is the number of observations and L is the vector strength. This test provides results comparable to chi-square (Curray, 1956; Evans, 1974).

In the analysis of former glacier source walls where different results may be obtained by varying the sectors chosen for chi-square computation, the Rayleigh test appears most suitable. However, since vector analysis requires a circular-normal distribution that may not always be the case, a further statistic has been evaluated by Dale and Ballantyne (1980). This statistic overcomes the problems inherent in the chi-square test for circular distributions and has no normality requirement. The A_n statistic was introduced by Ajne (1968), its percentage points were determined by Stephens (1969), and it is used to test for significance against a random distribution. The individual data points are transferred onto a circle of unit circumference and the test statistic is given by

$$A_n = \frac{1}{n} \int_0^1 (N(x) - \tfrac{1}{2}n)^2 \, dx \qquad (7.5)$$

where n is the number of data points, and N(x) is the number of points x_i ($i=1,2,\ldots,n$) that fall in the half-open interval $(x, x+\frac{1}{2}]$ between any point x and the point diametrically opposite.

Watson (1967) evaluated the integral as

$$A_n = \frac{1}{2} - \frac{n}{4} + \frac{2}{n} \sum_{j=2}^{n} \sum_{i=1}^{j-1} \left| x_j - x_i - \frac{1}{2} \right| \qquad (7.6)$$

which is readily calculated using a simple FORTRAN computer program written by the present author. Significance tables are given in Dale and Ballantyne (1980).

In this study the cumulative vector and its strength will be used where appropriate to describe the data and to compare the regions of the field area. The Rayleigh significance test and the A_n statistic will be employed to test the significance of the clustering found.

The Azimuthal Distribution of Former Glacier Source Walls

The aspect of the mid-point of each rock wall is assumed to be representative of the whole wall. It was abstracted from the map with an accuracy to the nearest 22.5° (see Chapter 2) and formed the basis of the analysis. The distribution of aspect over the whole field area is indicated in Table 7.1. The table

Table 7.1 Orientation of Former Glacier Source Walls

Direction ($^{\circ}$)	n	% of total
North (337.5- 22.5)	124	27.1
NE (22.5- 67.5)	124	27.1
East (67.5-112.0)	94	20.5
SE (112.5-157.0)	28	6.1
South (157.5-202.0)	15	3.3
SW (202.5-247.0)	9	2.0
West (247.5-292.0)	14	3.1
NW (292.5-337.0)	50	10.9

shows that the sectors centred on NE and north are most commonly represented, each containing over 27% of the total, and that less than 9% of all rock walls face between south and west. Fig. 7.1, which shows the information diagrammatically, indicates a strongly clustered distribution. In Fig. 7.2 the cumulative vector has been drawn: the resultant direction was calculated using Eqn (7.1) and a value of 35.3^{0} was obtained with a vector magnitude of 252.2m and a strength of 55.1%. According to Evans's (1977) interpretation of vector strength this represents marked asymmetry on a five-point linear scale whose categories range from symmetric through weak, marked and strong to extremely asymmetric distributions. Using the Rayleigh significance test (Eqn 7.4) the distribution differs from random at a level greater than 0.001.

In order to study the role of aspect more closely the total population was divided into regional components for comparison. Rose diagrams for each region are shown in Fig. 7.3 and resultant vectors together with their strengths are given in Table 7.2. Quite striking variations are indicated between

Table 7.2 Regional Resultant Orientations

	resultant vector	R	L	Evans's scale	p
SE Grampians	56.6	27.6	54.6	marked	$2.0114.10^{-6}$
Cairngorms	48.9	19.9	42.3	marked	$2.2270.10^{-4}$
W Highlands	17.1	112.7	70.0	strong	$5.4766.10^{-35}$
SW Grampians	55.5	51.4	55.3	marked	$4.4521.10^{-13}$
Monadhliath	55.1	26.1	65.3	strong	$3.9131.10^{-8}$
Skye and Rhum	23.7	28.2	47.9	marked	$1.3515.10^{-6}$

regions. The regions towards the west (Skye and Rhum and the mainland west of the Great Glen) exhibit a much stronger northward component in their azimuthal distribution than those farther east, which do not vary greatly from each other. Vector strength varies considerably although it always produces highly significant probabilities using the Rayleigh significance test.

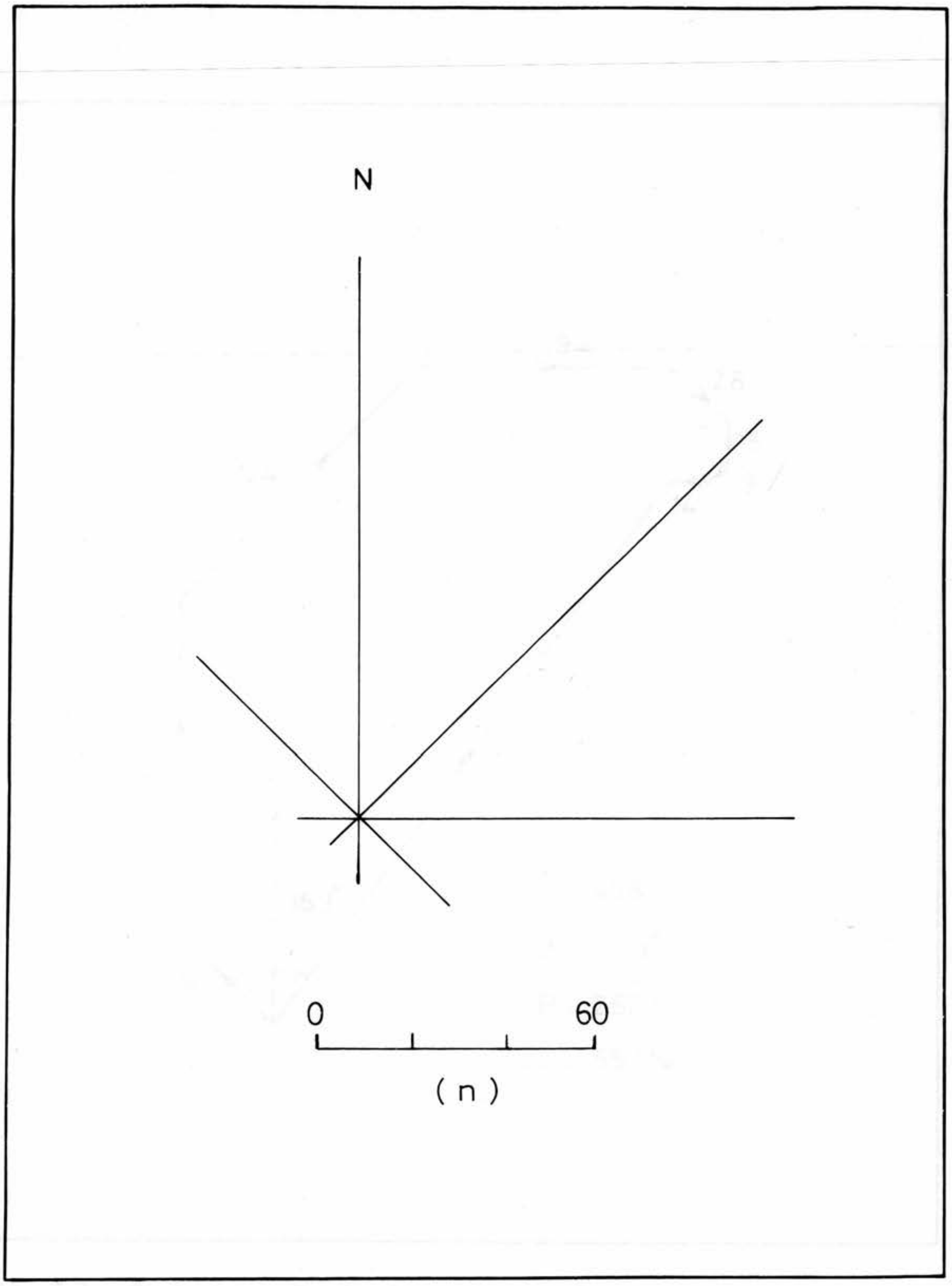


Fig. 7.1 Azimuthal Distribution of Rock Walls

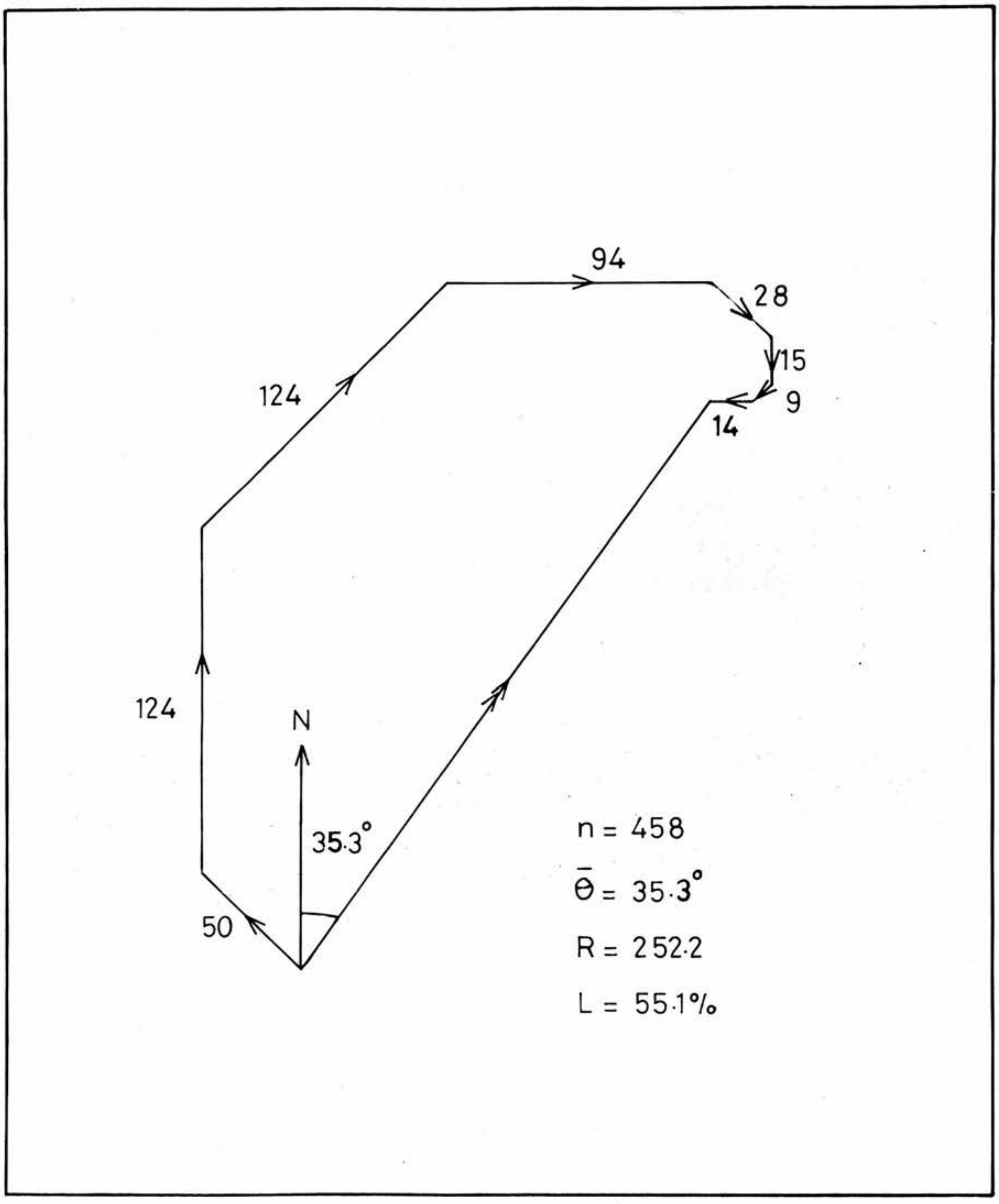


Fig. 7.2 Study area: Cumulative Vector ($\bar{\theta}$ = mean vector direction; R = vector magnitude; L= vector strength)

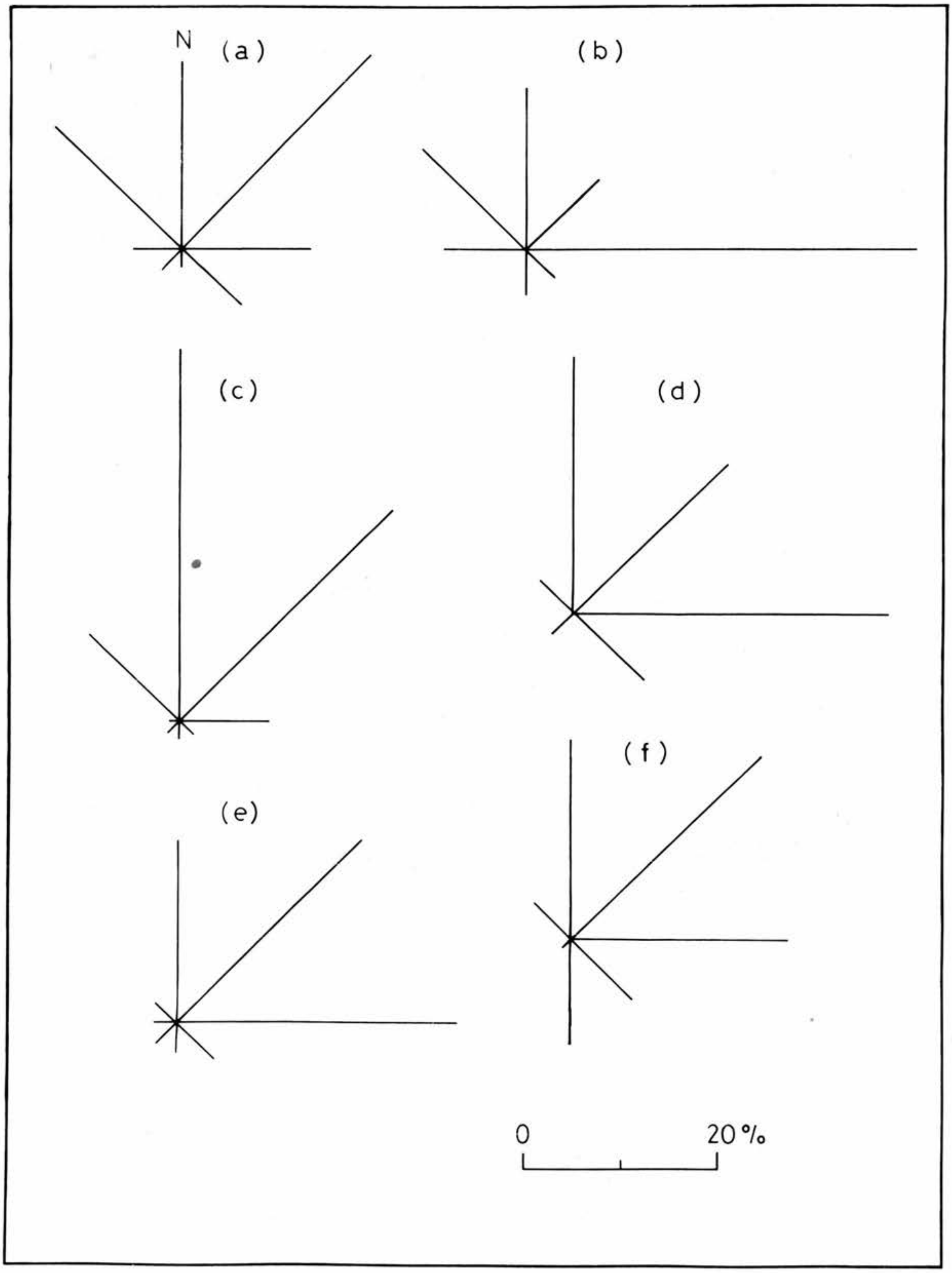


Fig. 7.3 Regional Azimuthal Distributions
(a - SE Grampians, b - Cairngorms, c - W highlands, d - Monadhliath, e - SW Grampians, f - Skye and Rhum)

The West Highland region produced the most markedly non-uniform distribution, the Monadhliath distribution also being strongly clustered. The Cairngorms produced the least asymmetric pattern.

From the rose diagram the Cairngorms appears to have a very sharp easterly mode, but the region also displays strong northerly and northwesterly secondary modes. This accounts for a resultant vector with a slightly more northerly component and a lower vector strength than found elsewhere. The rest of the regions east of the Great Glen have remarkably similar resultants (55.1^{o}-56.6^{o}). In the case of the Cairngorms vector analysis in not an altogether appropriate test of significance and the A_n statistics were applied. The A_n360 statistic, which considers the orientation of values about the whole circle is the appropriate significance test when the values are contained in approximately one half of the circle, as in this case (Dale and Ballantyne, 1980). The distribution in the Cairngorms is significantly different from random. Table 7.3 shows the A_n360 values obtained for each of the regions. As with the Rayleigh test the values are all significant.

Table 7.3 A_n360 scores, for each Region

	n	A_n360	p
SE Grampians	58	2.8060	<0.01
Cairngorms	46	2.0163	<0.01
W Highlands	161	16.8929	<0.01
SW Grampians	92	5.9511	<0.01
Monadhliath	39	3.3782	<0.01
Skye and Rhum	59	2.8941	<0.01

Another way of indicating the clustered distribution of aspects is to aggregate the azimuthal information collected for every data point abstracted at 100m intervals along the crest of each wall. The aspects of the 5067 points emphasis the strong northeastward tendency in the data set. Table 7.4 shows that overall the greatest amount of wall faces NE rather than north,

Table 7.4 Aspects of Individual Rock Wall Segments

	n	%N	%NE	%E	%SE	%S	%SW	%W	%NW
SE Grampians	760	18	28	19	11	7	6	6	6
Cairngorms	570	15	24	21	13	9	2	5	12
W Highlands	1485	34	30	5	6	3	1	4	17
SW Grampians	1077	19	26	28	10	3	1	2	10
Monadhliath	406	18	26	22	17	6	3	2	7
Skye and Rhum	769	19	24	14	10	3	5	9	15

although N and NE share the same number of mid-point values. South, SW and west increase their proportion of the total since although the mid-points of rock walls rarely face in any of these directions they contribute as 'sidewalls'. Again, a very large proportion of the former glacier source walls in the West Highlands face northwards and very few face between south and west. The Cairngorms show no secondary modes when all rock wall crest points are considered, presumably since wall segments facing NE may contribute to rock walls facing either easterly or northerly directions. Because sidewalls are consequent on the erosion of the rock wall in a direction ordained by the processes involved, the mid-point aspect rather than all wall segment aspects has been used in much of the following analysis of the azimuthal distribution of former glacier source walls.

The Azimuthal Distribution and its Relationship to Rock Wall Elevation

Polar diagrams such as used by Seddon (1957) were constructed to illustrate the altitudinal distribution and orientation of rock walls in each region of the study area. In order to spread the values out from the eight aspect classes used, and to weight the values in terms of the number of wall segments facing in each direction, the resultant vector for each wall was calculated as indicated above. The vector direction, its magnitude and strength for each former source wall are given in Appendix 2. The polar diagrams for each region are shown in Fig 7.4. On first inspection there is little apparent relationship between azimuth and altitude for any region. In the SE Grampians the lowest rock walls occur in the NE quadrant, which is also the quadrant with the largest number of occurrences. The group of SW-facing walls occurs at altitudes in the middle of the range from just below 600m to 800m. Only one rock wall falls in the SW quadrant of the Cairngorms diagram (Fig. 7.4) and this is the highest rock wall in the entire study area (1153m). Rock wall elevations are most widely spread in the NW quadrant and least in the SE. The West Highland diagram shows a clustering of points in the northern hemisphere with a few azimuths in the southern hemisphere at middle to high elevations (460-1020m). The SW Grampians has a cluster of points in the northeastern hemisphere with very few lying between SE and NW (moving clockwise). The Monadhliath region has only one rock wall in the SW quadrant and it occurs at an altitude about average for the rest of the diagram. Within the northeastern hemisphere there does not appear to be much variation in the range of rock wall elevation. In Skye and Rhum the NE quadrant contains the lowest rock walls, the minimum level rising in both directions from here. The SW quadrant, however, contains rock walls at less than average height for the NE quadrant. Clearly there is no straightforward relationship between rock wall azimuth and altitude.

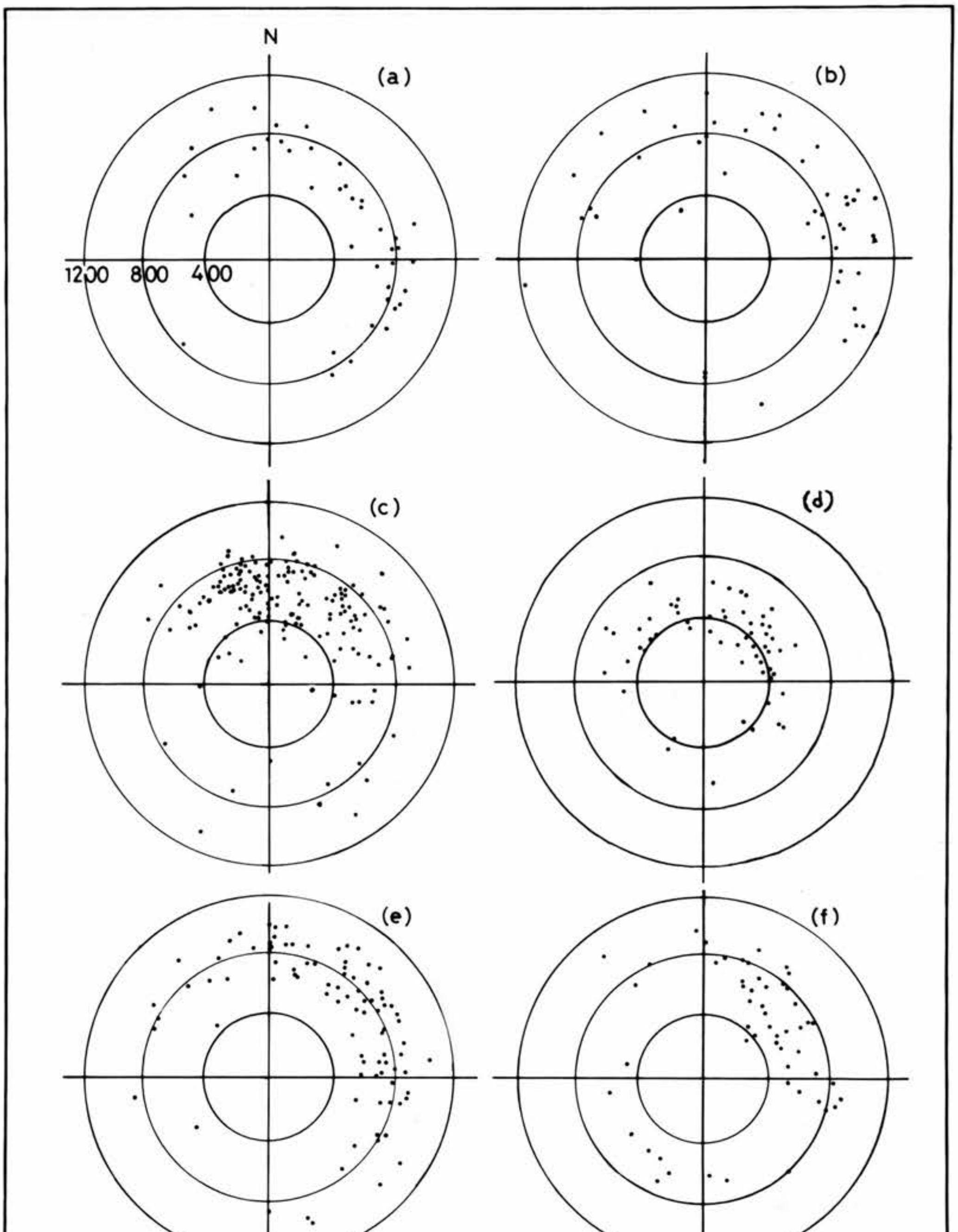


Fig. 7.4 Relationship of Altitude and Aspect in each Region
(a - Monadhliath, b - Cairngorms, c - W Highlands, d - Skye and Rhum, e - SW Grampians, f - SE Grampians)

The Distribution of Cirques in the British Isles and Western Europe

The azimuthal distribution of former glacier source walls in the study area is similar to the distribution of cirques found by other workers in Scotland. For 437 features given by Sissons (1967), Evans (1969) calculated a resultant vector direction of 48.1^{o} with a strength of 50.7%. Sale (1970) presented information on the aspect of 876 features he deemed to be cirques in Scotland. For comparison, the present author calculated the resultant vector azimuth and strength using these data and Eqns (7.1) and (7.2). An azimuth of 43.6^{o} was revealed with a strength of 24.3%. The low vector strength, indicating only a weak clustering, probably reflects inconsistencies in the data.

Analysis of cirque orientation has also been carried out by various authors over parts of the present study area. Sugden (1969) studied cirques in the western Cairngorms. He noted a bi-modal distribution of orientation with maxima at NNW and east, and related these to different sizes of cirque. By introducing a simplistic correlative model between size and age he suggested that the larger group, which faces between north and east, is the older. There is, however, no satisfactory evidence for this. A less demanding explanation is simply that more than one set of influences has worked to form cirques, resulting in more vigorous erosion of east-facing cirques and/or they have been occupied for a greater length of time. Evans (1977) used Sugden's data to produce a resultant vector for the area of 47^{o} with a strength of 57%.

The present study also indicates a bi-modal distribution of rock walls in the Cairngorms and the relationship with rock wall area was investigated by plotting a polar diagram of area and orientation for the Cairngorm region (Fig. 7.5). In this

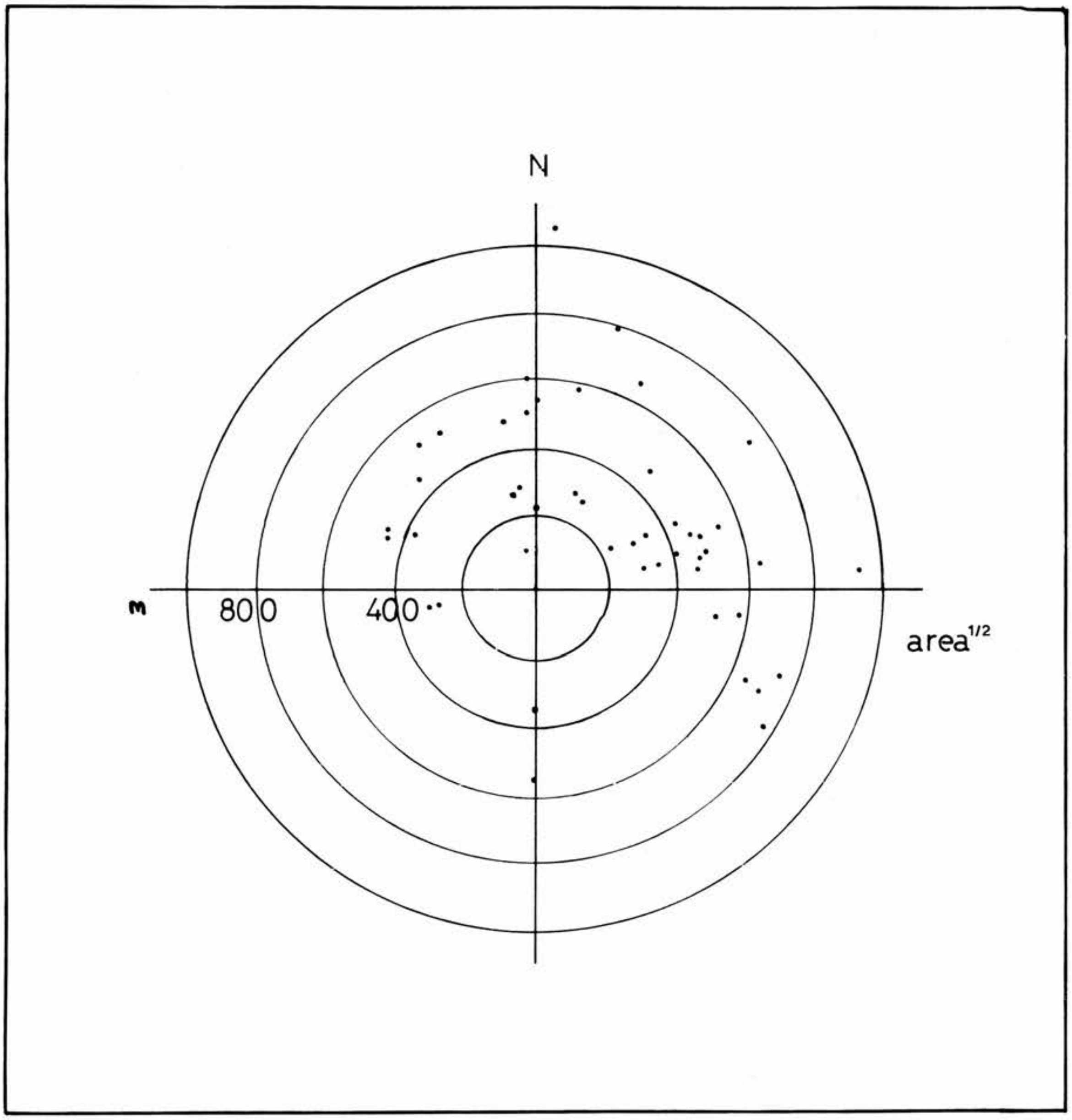


Fig. 7.5 Rock Wall Aspect and Area in the Cairngorm Region

diagram area is represented by its square root because of its high positive skew. The distribution of rock wall areas does vary with azimuth. There is a limited range of rock walls facing NW whereas there is a wide spread of values of rock wall areas with easterly azimuths. Several of the small (less than $0.16km^2$) east-facing rock walls lie along the west side of the Glen Einich trough and although they are true rock walls (see Fig. 3.6) they are not sufficiently developed laterally to be called cirques and therefore were not included in Sudgen's study. The simplest explanation for their poor downstream development lies in their location along the side of the trough, the ice that eroded this inhibiting the rock wall ice erosion. This explanation was used by Derbyshire (1963) to explain the poor development of certain cirques in Tasmania which lay below the snowline. With this interpretation the need for an explanation such as that proposed by Sugden is obviated.

In the Kintail-Affric-Cannich area of Scotland, which includes the NW of the present study area, Gordon (1977) calculated a mean long profile azimuth of 52^{o} with a vector strength of 57% for 231 simple cirques. This figure is substantially different from that for rock walls in the West Highland region of the field area and reflects differences between rock wall azimuth and the cirque long profile azimuth, the latter being influenced by structural and topographic factors as well as rock wall erosion.

Godard (1965) also analysed the cirques of the NW Highlands. For 437 cirque long profiles located between Mull and Orkney a resultant vector of 48^{o} was found with a vector strength of 51%. This is similar to the figure calculated by Gordon but is also probably affected by the aspect of the whole cirques rather than by the headwall, which is the part most intimately associated with the processes of glacier accumulation and glacial erosion.

Thorp (1979) studied 46 cirques in the Ben Nevis and Mamore Forest ranges of the SW Grampians. From the azimuthal distribution given in classes composed of a quadrant each, the present author calculated the resultant vector as 56^{0} with a strength of 58%. These figures are very similar to those found for rock wall azimuths in the SW Grampians Region as a whole (Table 7.2). The vectors for each of the areas studied by the above authors are summarised in Fig. 7.6. The values are all contained in a small part of the NE quadrant compared to rock wall resultant vector azimuths which are scattered about the quadrant.

The Scottish cirques and rock walls fit into a wider pattern of cirque azimuths in the British Isles and western Europe. Early studies examined examples from many locations. For example, Lewis (1938) showed the clustered distribution of a sample of 44 British cirques in the northeastern sector of a polar co-ordinate diagram. Similarly, Enquist's (1916) classic study suffers from the sampling technique, which allowed him to pick out good examples of rock wall azimuthal clustering because of drifting to lee positions. However, because he selected only certain cirques their unrepresentativeness led him to incorrect inferences on the reason for the clustering. More recent studies have considered the total population of cirque aspects in whole mountain groups and are more satisfactory from the methodological point of view.

Although Evans (1977) has performed the useful task of collating cirque aspect data world-wide and presented them in a form suitable for comparison, the patterns displayed by the results in their relative geographical locations have not been discussed. Here, data from the northwestern fringe of Europe are assembled and examined in terms of their locations in space. Calculations similar to those carried out by Evans (1977) have been made where necessary to make the data

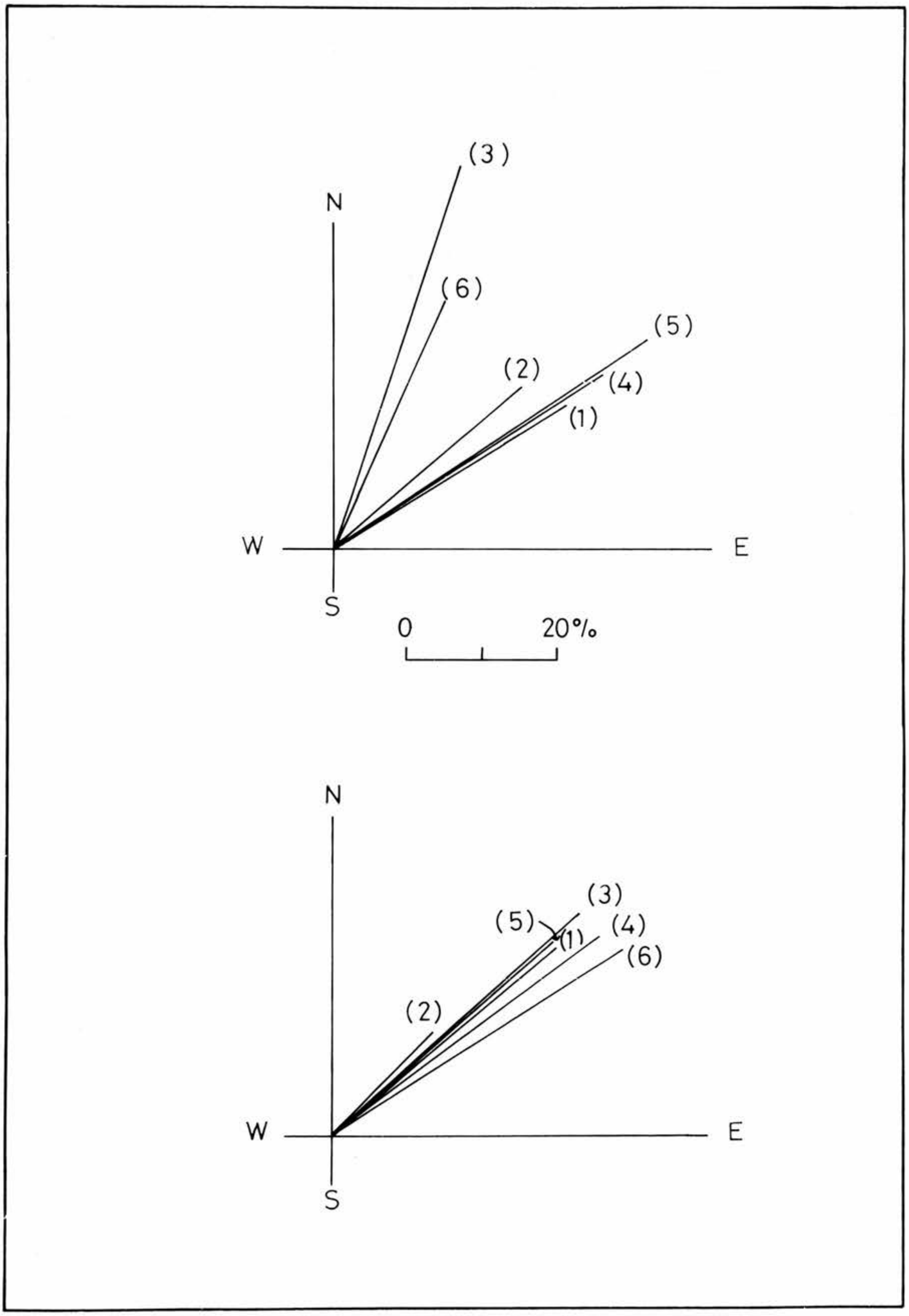


Fig. 7.6 Rock Wall and Cirque vector directions and strengths in Scotland (a) rock walls(1-SE Grampians, 2-Cairngorms, 3-W highlands, 4-SW Grampians, 5-Monadhliath Mts, 6-Skye and Rhum); (b) cirques (1-Scotland, Sissons(1967), 2-Scotland, Sale(1970), 3-Cairngorms, Sugden(1969), 4-W Highlands, Gordon (1977), 5-W Highlands, Godard(1965), 6-Ben Nevis, Mamore Forest, Thorp(1979))

comparable, and the information is contained in Table 7.5 and Fig 7.7. These figures show a surprisingly consistent trend throughout this wide area: except in coastal Norway the former glacier source walls and cirques display a resultant vector lying east of north and in many locations show a high vector strength. The vector directions lie outside the NE quadrant only at very high latitudes. There appears to be a west-east trend in that the rock walls in locations closest to the Atlantic Ocean (i.e. West Norway, West Highlands of Scotland, Skye and SW Ireland) have vectors much closer to north than in the mountain groups farther away. This is most noticeable in the British Isles, where the greatest amount of data has been collected. Pippan (1965) found the same pattern across Norway however, with an increasingly easterly component in the resultant vector moving away from the Atlantic coast.

The Influence of Structure and Topography on Rock Wall Aspect

The distribution of cirque aspects is most commonly attributed to elements of the climatic environment during erosion. However, other factors such as the alignment of topography and the geological structure are significant. Andrews (1965) concluded that the azimuthal pattern of certain cirques in Labrador is related to the alignment of anorthosites in which they are eroded, although climate also has an important role in separating those that contain glacier ice and those that are empty. Schwan (1974) reported several dominant modes of cirque orientation in the Hautes Vosges, one of which occurs at 330^{0} and coincides with a Hercynian main fault trend. He presumed the remaining modes lying between 0^{0} and 90^{0} are due to the influence of shade and wind drifting of snow into these sites. However, structure does not appear to play an over-riding role in the study area since rock wall groups in quite diverse geologies display the same regional aspect trends.

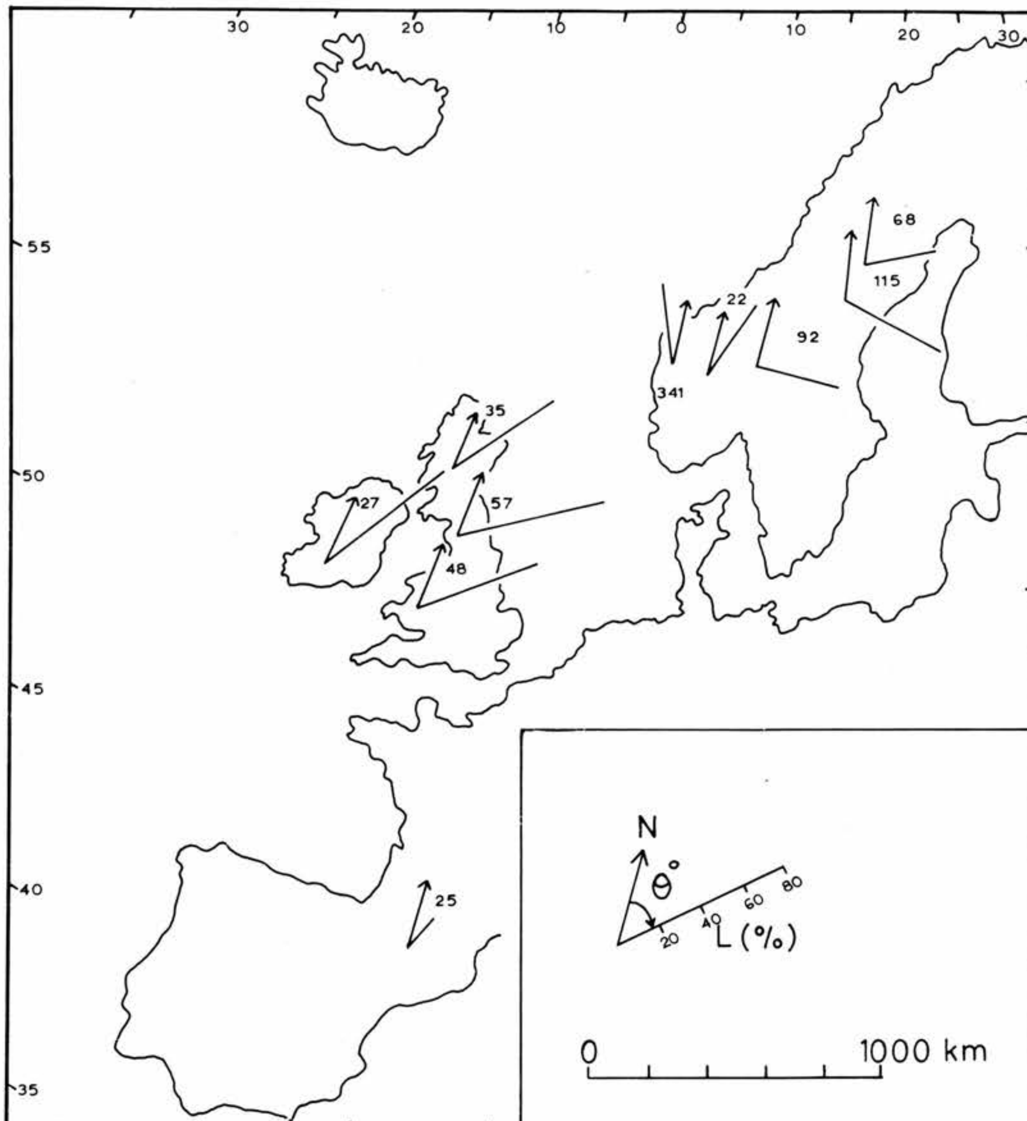


Fig. 7.7 Aspect of Cirques and Rock Walls in W Europe

Table 7.5: Rock Wall and Cirque Aspects in North-West Europe

location	Source	Measurement	n	θ^o	L(%)	Source of Calculation
Great Britain						
Scotland	Sale (1970)	Cirque Long Profile	876	44	24	Dale
Kintail-Affric-Cannich	Gordon (1977)	Cirque Median Axis	231	52	57	"
NW Highlands	Godard (1965)	Cirque Long Profile	437	48	51	"
W Highlands	Dale	Rock Wall Mid-point	161	17	70	"
Skye and Rhum	"	" "	59	24	48	"
Monadhliath Region	"	" "	40	55	65	"
SE Grampians	"	" "	58	57	58	"
SW Grampians	"	" "	93	56	55	"
Cairngorms	"	" "	47	49	42	"
Western Cairngorms	Evans (1974)	Cirque Long Profile	22	47	57	Evans (1974)
Ben Nevis, Mamore Forest	Thorp (1979)	Cirque Median Axis	46	56	58	Dale
West-Central Lake District	Temple (1965)	Cirque Long Profile	73	48	47	"
Lake District	Clough (1977)	Cirque Median Axis	112	57	63	"
Snowdonia	Unwin (1973)	Cirque Median Axis	81	48	57	Unwin (1973)

Table 7.5 (cont'd)

Location	Source	Measurement	n	θ°	L(%)	Source of Calculation
N Wales	Seddon (1957)	Cirque Moraine Aspect	34	45	72	Evans (1974)
SW Ireland	King and Gage (1961)	Cirque Long Axis	34	27	64	"
Scandinavia						
Swedish Lapland	Vilborg (1977)	Cirque Long Profile	1277	68	32	Dale
S Lapland, Sweden	Soyez (1974)	Cirque Long Profile	113	115	40	"
Västerbotten, Sweden	Evans (1974)	(1)	93	125	47	Evans (1974)
Jötunfjelds, Norway	Helland (1877)	(1)	37	12	66	Evans (1974)
Jötedalsbreen, Norway	"	(1)	41	16	61	"
Jotunheim, Norway	Pippan (1965)	Cirque Orientation	(2)	22	36	"
Coastal Norway	"	" "	(2)	341	37	"
Eastern Norway	"	" "	(2)	92	35	"
Pyrenees	Chevalier (1955)	Cirque Long Profile	83	25	18	Dale

Notes

(1) Unspecified

(2) Pippan (1965) values given as percentages

Topographic alignment, particularly in terms of the pre-glacial configuration of valley heads, may contribute to cirque and rock wall aspect. Trenhaile (1977) studied cirque locations and produced a model to explain cirque aspect in this way. The marked clustering of rock wall aspects in the West Highland Region at 18^{o} may be related to a topography that is dominated by ridges mainly aligned east-west as indicated for example by Haynes (1977, Fig.6). Obviously, the possibility of rock walls facing either east or west is diminished, in comparison with either north or south. The almost total lack of south-facing glacier source walls in the West Highland Region and the existence of the same general resultant vector altitude in the very different topographic configuration of Skye suggests that topographic alignment is not a paramount factor. Evans (1974) considered that in dealing with the aspect of cirque headwalls, rather than that of cirque long profiles, structural and topographic effects are greatly reduced. These are minimised further in a study of glacier source walls. The way in which climate influences rock wall azimuthal distributions are considered now particularly in terms of the distribution across the field area. Overall this distribution is highly clustered (markedly asymmetric) but displays an increasing easterly component towards the east.

The Climatic Factor in Rock Wall Aspect

The factors that influence the aspect of glacier source walls are essentially those that influence glacial mass balance in the accumulation area of a glacier. Evans (1977) listed these as radiation, wind direction and to a lesser extent contrasts in atmospheric conditions between morning and afternoon. An important proviso is that glaciers are a short-term response to climatic environment, whereas rock walls are a result of the interaction of these responses and the process of erosion on many occasions.

(i) The influence of radiation

Global radiation (i.e. direct insolation plus diffuse radiation) is frequently the most important energy source available to a glacier (Paterson, 1969, p.49) and is the only one to vary significantly with surface irregularities (Ohmura, 1968). The intensity of radiation at the surface for any latitude varies with altitude, atmospheric absorption, surface absorption or albedo, and the surface slope angle and orientation (Geiger, 1969). Although Lebedeva (1971) showed that at high altitudes the amount of global radiation received at the surface increases with altitude because of less atmospheric absorption and reflection, this effect is considered negligible in the field area because of the comparatively low mountain elevations and the small range of altitudes. Also, since the quantity of diffuse radiation reaching the surface is affected only by atmospheric absorption and the proportion of the sky open to the surface, assuming an isotropic atmosphere, this part of the available global radiation does not influence the orientation of glaciers. Consequently, if incident radiation consisted only of diffuse energy, glacier accumulation areas and rock walls would not have a preferred orientation for this reason. This situation can be envisaged if skies were predominantly cloudy during the daytime in the ablation season.

Direct insolation varies with aspect and slope angle, the variability being largest in cloudless conditions. Kondratyev (1969) considered the solar income of sloping surfaces. He showed that the radiant flux received by a sloping surface is

$$S_{SL} = S_m \cos(i) \qquad (7.7)$$

where S_m is the solar flux received at the earth's surface on a perpendicular plane, and i is the angle of incidence of the solar rays on the surface. Kondratyev and Manolova (1960) demonstrated that on slopes up to 10^0 the amount of radiation received is almost independent of slope orientation. However, for steeper slopes S_{SL} varies with the cosine of the angle of incidence. This is dependent on the solar altitude and on the orientation and slope of the surface. The angle of incidence also affects that part of the beam that is reflected from the surface. Least is reflected from a plane perpendicular to the flux but the proportion increases as the angle of the incident rays tends to parallel the ground surface slope (Andrews, 1971).

The importance of differences between aspects varies throughout the year. Borzenkova (1967) found that annually a south-facing slope inclined at 30^{o} receives around 25% more radiation than a horizontal plane while a similarly inclined north-facing slope receives 40% less. However, he did not state to which latitude these figures apply. The greatest difference is in winter and the difference is least in summer when the altitude of the sun is higher, the seasonal difference being largely accounted for by the period of the year when the sun may be continuously below the local horizon for north-facing slopes. Since glaciers often occur below or against steeply-sloping rock walls this is a common situation. Shading of these glaciers from direct insolation has long been thought to make an important contribution to their situation (Embleton and King, 1975, p.222; Andrews et al, 1970). Borzenkova (1967) reported the work of fellow Russians who have tried to theorise on the influence of surrounding topography but in the main it is not possible to generalise. Few empirical studies have been carried out to assess the importance of shading in individual sites.

The melting of snow and ice is directly dependent on air temperature rather than the receipt of radiation. The time of day, therefore, at which a slope receives any or most of its radiation is important. SE-facing slopes receive their maximum insolation early in the day whereas SW-facing slopes are irradiated after midday, when the ambient air temperature has reached its peak. Thus a SW slope is less favourable to glacier mass balance than a SE one in maritime locations where afternoon cloudiness is not such an important factor as in continental locations.

In summary, with increasingly cloudy conditions variations of insolation received on slopes facing different directions decreases to a minimum because differences due to both slope and shade factors are diminished. Similarly differences are also minimised in summer (Fig. 7.8). Because of their relative cloudiness, during the ablation season, the effect of insolation in maritime locations is less than elsewhere.

(ii) The influence of wind direction

The second factor that influences the aspect of glacier source walls is the direction and dominance of the prevailing wind which distributes precipitation and redistributes fallen snow from higher locations to lower more sheltered locations. Enquist (1916, pp.8-23) was one of the first to examine this effect in detail, taking examples from many northern and southern hemisphere locations to show that accumulation on lee slopes was a factor more important than insolation protection in the siting of small glaciers.

The variability of precipitation distribution occurs at two different spatial scales. Greatest amounts tend to be dropped on the windward sides of large mountain ranges due to the forced uplift of air here. This large scale variability in precipitation distribution is often apparent at the present day in the study area. For example, with southerly winds across the Highland Boundary in winter, this area may be well covered with snow, but farther north, at higher altitudes, little snow may have fallen and skies are clear. In the last chapter large scale gradients in precipitation were envisaged to account for

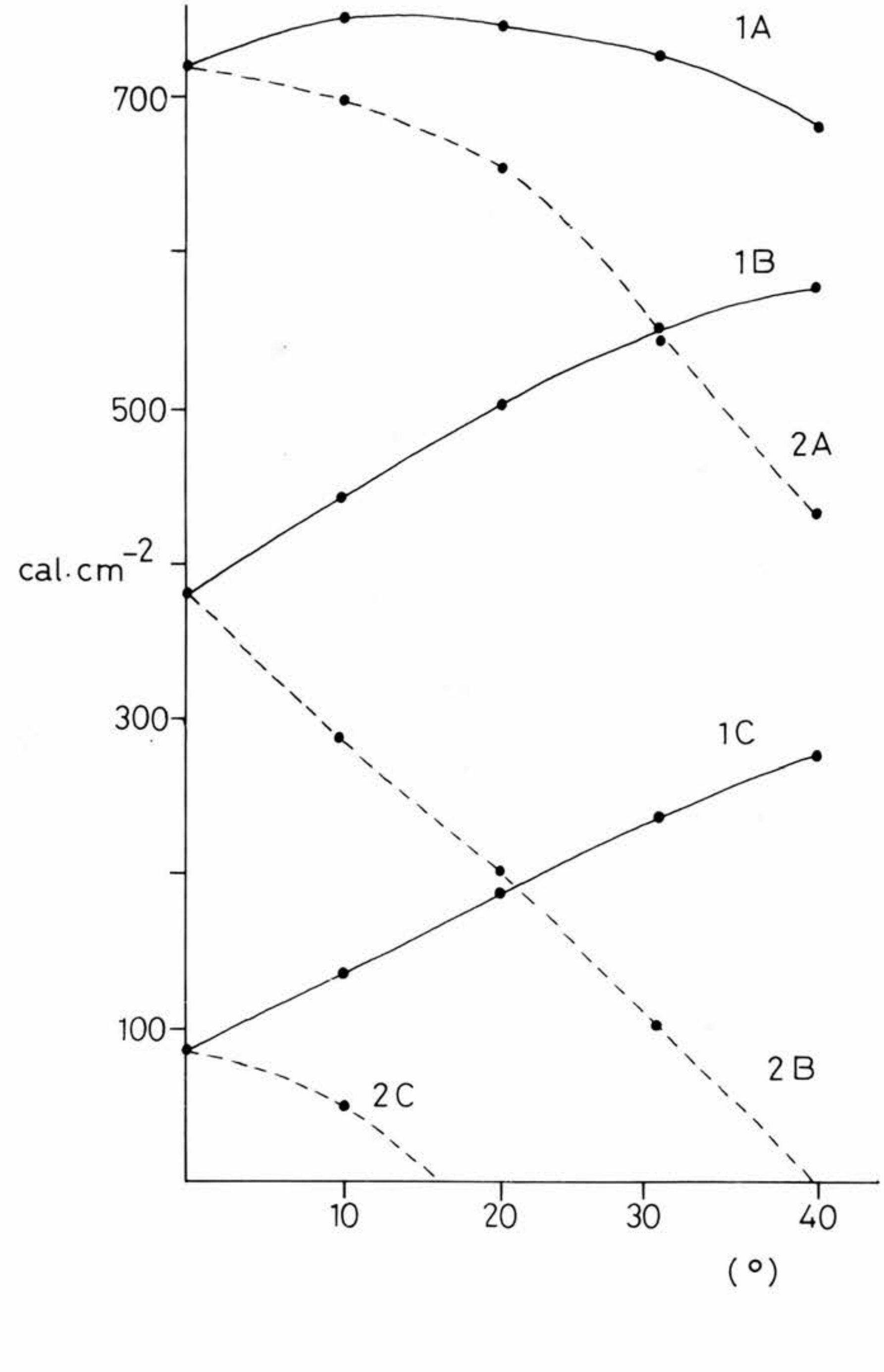


Fig. 7.8 Daily heat totals for southern and northern slopes (50°N) (1 = south-facing slope, 2 = north-facing slope, A = June 22, B = March 22, September 22, C = December 22; data after Kondratyev (1969))

the rise in rock wall base altitudes with distance from the west coast or the Highland Boundary during periods of rock wall formation.

The second factor to cause variability in the precipitation pattern is much more local in character. Irregularities in topography cause variations in the wind pattern and its strength, thus enhancing the drift of snow from exposed sites to more sheltered positions on the lee side of upstanding obstacles. Variations in wind speed due to pressure differences caused by topographic roughness have been discussed by Gloyne (1964). He showed that back eddying occurs downwind on the lee side of any abrupt topographic change for a distance proportional to the change in elevation of the surface at the obstruction. Although Gloyne was primarily concerned with artifical shelter belts, the analogy with rock walls and the accumulation of snow and ice is obvious. A fairly frequent pattern, particularly in the rolling plateau regions of the study area, is gentle up or down slopes giving way to abrupt breaks of slope at the rock wall crest. Wind velocity immediately drops and the load of snow carried in the lower levels of the atmosphere is deposited. Derbyshire (1968) called ridges aligned transverse to the prevailing wind direction 'snow fences', these aiding the accumulation of snow and eventually glacier ice on their lee sides. Manley (1959) observed the back eddies caused by the rock wall affecting the regional air flow illustrated by the ripple patterns on Lake District tarns when the regional wind was in the opposite direction. Eddying due to the disturbance of the wind pattern has also been observed on present day cirque glaciers. Hollows up to 15m deep were observed by Grove (1960) on Veslgjuvbreen due to eddying. Studies to improve the catchment of winter snow for reservoir use have been made in the eastern Rockies. Martinelli (1973) showed how the introduction of artificial snow fences can increase the collection of snow in banks on their lee sides.

Accumulation due to the dropping of snow on lee sides of mountains or the redistribution of snow from exposed upland sites to sheltered lee concavities is most effective in the accumulation of snow banks. These will be placed exactly in the lee of the prevailing winter winds. However, glacier ice has also to contend with the effects of insolation during the ablation season and therefore sites are the aggregation of these two factors. For wind drift to be important in rock wall aspect a wind consistently from the same direction is required.

Despite these drawbacks numerous examples of the existence of glaciers due to accumulation on the lee sides of obstacles may be cited. Dolguishin (1961) described glaciers on the east and NE sides of the Polar Urals that owe their existence to the drifting of snow to sheltered lee locations. Similarly, in the Caucasus, Kotliakov and Touchinski (1974) found snow drift makes an important contribution to glacier accumulation. Obviously, the actual amount of snow blown onto glaciers varies with location. Hoinkes (1964, p.394) reported much Russian work and indicated that on average 20% of the accumulation on cirque glaciers may be due to drifting. Kotlaikov and Touchinski (1974) gave an example of the transport of 100,000 tonnes of snow through a distance of 1km, although such transport must be extremely difficult to measure. In an attempt to reconstruct Loch Lomond Advance glaciers in the SE Grampians, Sissons and Sutherland (1976) estimated conservatively that 5% of the accumulation of cirque and valley head glaciers was due to drifting from upland plateaux.

A further aspect of air flow is the drainage of cold air into topographic concavities (Geiger, 1965, p.195), thus lowering the temperature at the start of the diurnal cycle. The lack of vertical mixing in sheltered locations also allows the lowest layers of the atmosphere to become very much cooler than elsewhere.

The Strength of Clustered Distributions of Rock Wall Aspect

Direct insolation and wind drifting of snow in the northern hemisphere combine to concentrate the azimuthal distribution of independent accumulation areas to the east of north. The degree of clustering or its strength varies because of variation in the processes that cause clustering. Evans (1977, p.196) was able to formulate 'a law of decreasing glacial asymmetry with increasing glacier cover'. This can be interpreted as meaning that as glaciation becomes less marginal the degree of azimuthal clustering becomes less and glaciers hitherto inhibited from accumulating in certain aspects can do so as the severity of climate increases.

Since temporal variations are not helpful in the present study it is more useful to translate this statement into altitudinal or spatial terms. For altitudes above the snowline, the dependence of glacier source areas on shade and wind drift decreases with elevation for, over a wide range of increasing altitudes, precipitation rises and temperatures fall. Therefore within a fairly small mountain area (to minimise regional elevation trends) it is reasonable to postulate that the azimuths of source walls should become less clustered with altitude above the snowline. The polar altitudinal diagrams drawn for each region (Fig. 7.4) indicate that this is only partially true. There is not a clear decrease in clustering of azimuths with increase in altitude in each regional diagram. There does tend to be the greatest range in altitudes of rock walls in the northern hemisphere of each circle, although this could be an expression of the greater number of rock walls contained in this hemisphere. In each region, the lowest rock walls are contained in the northern hemisphere, and for Skye and Rhum and the SE Grampians, particularly in the NE quadrant. However, across the field area there is no general increase in altitude with azimuth away from this sector, but there tends to be a middle altitude band that contains the rock walls with aspects in the southwestern quadrant. This is contrary to Trenhaile's (1976) model for the Canadian Corderilla in which he found that cirques at elevations high above the snowline, although small, were independent of orientation.

Table 7.6 gives the mean rock wall altitude for every orientation group in each region. This shows the surprising result that in several regions SW- and west-facing rock walls occur at low altitudes, compared with the much wider range of altitudes occurring in other directions. This lends support to Evans's (1974) thesis that unfavourable aspects may only support glaciation when the snowline has been greatly depressed.

Table 7.6 Mean Rock Wall Base Altitude for each Aspect

	Altitude (m)							
	N	NE	E	SE	S	SW	W	NW
SE Grampians	761	639	646	670	675	588	576	825
Cairngorms	895	857	894	921	765	-	935	855
W Highlands	662	673	671	766	758	824	405	664
SW Grampians	831	831	769	784	920	702	829	723
Monadhliath	843	682	792	740	-	759	-	-
Skye and Rhum	484	469	444	450	649	439	598	501

Here there is an apparent contradiction: rock walls tend to be least clustered at middle to high elevations yet rock walls facing unfavourable aspects only occur when the regional snowline is greatly depressed. The contradiction may be resolved by considering the differences between rock wall and glacier aspects. Close to the snow line only those sites or rock wall locations favourable in terms of accumulation and ablation will become occupied by glacier ice. As the snow line is depressed farther these glaciers will themselves grow out from their initial sources and may assume an aspect governed by factors other than the initial climatic ones and the azimuthal distribution of the glaciers may well become less clustered. However, on the disappearance of the ice the rock wall azimuthal distribution remaining represents the distribution of aspects most favourable to glacier accumulation at the onset of the lowering snowline.

The Location of Rock Walls of Varying Aspects

The rock walls that face seemingly unfavourable aspects for accumulation and preservation of snow and glacier ice tend to occur in particular locations as well as at lower than average elevations. Rock walls with azimuths lying in the SW sector of the polar orientation diagrams (Fig. 7.4) tend to occur on the south or west sides of upland masses as well as on the south or west sides of individual mountains. Of the 15 former glacier source walls on the mainland that have a mid-point aspect between south and west (in effect between 157^{o} and 212^{o}) five occur in the SE Grampian plateau along the NE side of Glen Clova. It may be inferred from the trend analysis of rock wall base altitude (Chapter 6) that these rock walls lie on the windward side of the plateau and that they have benefitted from the 'plastering on' of snow during orographic and frontal precipitation. As was discussed earlier, orographic precipitation tends to be highest just to the windward sides of mountain masses.

The SW-facing rock walls occur in this situation in other regions also. In the West Highlands the rock walls with these azimuths lie close to the coast. In the Cairngorms, the only rock wall facing this direction occurs at 1153m on the east side of the Lairig Ghru, and on Skye the similarly-facing rock walls lie on the windward side of the Cuillins. Not only are these rock walls in favoured windward sites, and apart from the Cairngorm one at generally low elevations, but they are also in locations which, with a lowering of the snowline and a corresponding increase in glacier cover of the land surface would not have been rapidly over-run by glaciers emanating from sites that were occupied when glaciation was still marginal. The Skye and SE Grampians rock walls in the SW quadrant face away from the centres of ice build-up and the Cairngorm west-facing rock wall has a base altitude 550m above the present floor of the Lairig Ghru directly beneath it. Hence the SW quadrant has rock walls that are neither at the highest elevations (snow line too high) nor at the lowest, but that occur in special locations, which generally benefitted from precipitation, but also that were not over-run rapidly by ice from sites more favourably located during the initial lowering of the snowline.

The above pattern is largely the same as that found by Svensson (1959) in Scandinavia, where there are very few west-facing or windward cirques: where the latter do occur they are located towards the periphery of the main ice masses, along the western coastal margin. Elsewhere, Svensson surmised that inundation by valley and plateau ice with a lowering of the snowline impeded the normal development of cirque glaciers and the erosion of cirques with azimuths other than in the eastern quadrant.

The pattern of rock wall azimuthal distribution may be translated into spatial as well as altitudinal variations. It might be expected that in areas of less marginal glaciation the azimuthal distribution would become less clustered. However, consideration of the altitudinal distribution leads to a different conclusion. It is hypothesised that in areas where the snowline is rapidly depressed and glacial cover increases rapidly, valley and plateau ice that was initiated during marginal conditions in locations generally thought of as favourable may submerge sites in 'unsuitable locations' which later could contain their own glaciers. However, since ice does not then flow out from the latter sites, erosion towards features with the characteristics of rock walls does not occur. The extremely clustered azimuthal distribution of rock walls in the West Highlands may be interpreted in this way. In areas that continue to be marginal to glaciation azimuths other than those favourable for wind drift and insolation protection will occur only in peculiar sites, such as those exposed to much higher than average precipitation.

Several pieces of independent evidence concerning the onset of glacial conditions at the start of the Loch Lomond Advance suggest that the lowering of the snowline was indeed very rapid. Oceanic cores from the northeastern Atlantic suggest that the rate of movement of the polar water masses southwards at the onset of glacierization was extremely rapid. Ruddiman et al. (1977) inferred a mean rate of movement of $1140mm.y^{-1}$. Cores indicate that this rapid reversal from warm to cold conditions occurred several times previously.

The rapidity of the reversal that initiated the Loch Lomond Advance is corroborated by the macro-fossil evidence of the land surface temperature regime (Coope et al., 1971; Coope, 1975; Coope and Bishop, 1977). Fossil assemblages of coleoptera indicate a cooling in the July mean temperature in the English Midlands of about $9^{o}C$ in less than 1500 years (Coope, 1975).

Similarly, in view of the time available for the thermal decline at the end of the Lateglacial Interstadial, the geormorphic evidence suggests a rapid build-up of ice in Scotland to limits given by Sissons (1979a). The ice mass was largest in the western Grampians and the mountains west of the Great Glen. Thicknesses of 400m over the Rannoch basin were typical, and locally ice thickness may have been 600m (Sissons, 1974a). For this accumulation to occur in the time available a rapid depression of the snowline, particularly in the western Highlands must have occurred leading to a rapid build-up of ice cover, enveloping potential south- and west-facing discrete source areas at high altitudes. For this reason, in a part of the study area greatly suited to glacial accumulation, the greatest clustering of rock walls is found.

The degree of clustering of aspect is in agreement with the inferences made in Chapter 3 concerning the build-up of the ice sheets and ice masses in the southwestern part of the study area where there are very few rock walls. In that area, which has lower summit altitudes than farther north in the West Highland region (the latter having high rock wall densities with marked azimuthal clustering) it was argued, following the hypothesis of Ives et al. (1975) that discrete source areas with special advantages in terms of net accumulation were not required, build-up of ice being due to the contemporaneous accumulation of snow and ice over a wide area.

In contrast, on the Cuillins of Skye, the lowering of the snowline meant that potential source areas facing in all directions could act as accumulation areas as the snowline declined because for most periods of glacierization (e.g. the Loch Lomond Advance) these sites were not submerged by external ice. Many of the due west- and SW-facing cirques along the outer edge of the Cuillin ridge have, however, rock walls best developed on their NW- to north-facing sides, (Fig. 3.3), indicating even here the importance of protection from ablation and possibly the importance of southerly winds in the accumulation process during much of their occupation by eroding glaciers.

The azimuthal clustering in the western part of the mainland in the study area, is similar to that found in western Norway (Pippan, 1965) and SW Ireland (King and Gage, 1961). Although Pippan emphasised the importance of geological structure it is difficult to avoid the conclusion that, if the above discussion has validity, the inferences made for Scotland also apply to Western Norway.

Interpretation of Azimuthal Clustering

Over the whole study area the marked clustering of azimuths of former glacier source walls into the NE quadrant is caused by a combination of wind drift and lee accumulation, and insolation protection minimising ablation, plus the effects of increasing glacier cover in areas of rapid depression of the snowline. As already noted this pattern is found in almost all middle latitude locations in the northern hemisphere (Evans, 1977). In the southern hemisphere the pattern is more diverse. Clapperton (1971) reported 49 well-defined cirques in the Falkland Islands, 46 of which are oriented between NE and SE with a greater proportion in the NE quadrant than the SE. He concluded that the orientation pattern is due to winds prevailing during glaciation being predominantly southwesterly and having a greater significance than the insolation protection afforded by south-facing slopes.

Elsewhere in the southern hemisphere there is a tendency for cirques to be distributed about a south-easterly modal aspect (e.g. Galloway, 1963; Derbyshire, 1963), interpretation depending on the combination of insolation and wind direction. Since, apart from the Falkland Islands, these two factors tend to favour the same general azimuthal distributions the methodology employed until now can yield no fresh information concerning the relative importance of these factors to the climatic environment during glacial erosion of the features.

Returning to Fig. 7.1 however, some observations can be made. The rock wall azimuthal distribution is clustered about modes at north and NE. In much of the literature a northerly mode (in the northern hemisphere) is assumed to be indicative of the influence of direct insolation and a lag time must be introduced such that some azimuth west of south is less favourable to glacier ice than south itself. The maximum air temperature close to the ground occurs some 1-3 hours after midday and can be translated into a solar angle of 15-45^{0} west of south and it is this azimuth where most ablation would occur due to differential insolation. Thus rather than a symmetrical distribution about north, a symmetrical distribuion about NNE-NE would be expected. Fig. 7.1 does not conform to this although fewer former glacier source areas face SW than any other single aspect. Rotation of Fig. 7.1 30^{0} anticlockwise so that the least favourable aspect corresponds with south gives a distribution that is still asymmetric about the new 'north', with a larger proportion of the population occurring in the 'east' than the 'west'. Although insolation does play some role, wind and lee effects are clearly important.

The large variations between the regions certainly cannot be accounted for by solar radiation alone, the increasing easterly component of direction not being due to radiation. Any drying and warming of the air moving across the country and subsiding would lead to conditions less cloudy in the east and not more so. There should be an increase in clustering towards a more northerly aspect in the eastern regions if that were so, and this is the opposite of what is found.

Conclusions

1. Rock walls in the study area have a strong tendency to face NE. Across the area, the tendency varies from a direction with a more northerly component in Skye and the West Highlands, to an east of NE component in the rest of the mainland. This orientation pattern is consistent with that of cirques in the rest of NW Europe.

2. Evans's law of decreasing orientation clustering with increasing glacial cover is not of great value since temporal variations are not well documented in the field area. It is more useful if translated into altitudinal terms over short distances and across space.

3. The relationship between orientation and elevation is not as simple as that found by Trenhaile (1976) in the Canadian Cordillera. The least clustering of aspects is found in the middle altitude range in any region of the study area, and rock walls facing between south and west tend to have fairly low altitudes. This may be because many of the windward sides of mountain masses where the maximum precipitation is received are in positions last to be submerged by ice cap or valley ice, if at all.

4. The spatial pattern of rock wall aspects is not that which would be expected. The orientation distribution pattern of rock walls in the West Highlands (the area by all accounts most favourable for glacier build-up) displays the most clustered distribution around north of all the regions. Although this is partly a result of the topographic alignment it is inferred that it is also related to the rapid build-up of valley ice in this area which submerged potential sites initially in unfavourable aspects, except in locations peripheral to the ice centre. In contrast, on neighbouring Skye

where glaciers flowed outwards from the Cuillins all aspects are represented with few altitudinal variations. Elsewhere rock walls face between south and west only in locations with exceptional precipitation or at sites least likely to be inundated by external ice.

5. A different methodological approach is required to separate the effects of wind drifting to lee slopes and protection from ablation, although it is surmised here that the increasing easterly component of orientation towards the east of Scotland and Norway is related to the increasingly important role of drifting snow from upland plateaux to sheltered easterly-facing slopes. In the next chapter an attempt is made to understand the relative importance of wind and insolation protection and hence the climatic environment during periods of formation of glacier source walls.

CHAPTER 8

THE EFFECTS OF DIRECT INSOLATION AND WIND DRIFTED SNOW ON THE AZIMUTHAL DISTRIBUTION OF ROCK WALLS

Introduction

In the last chapter several reasons were proposed for the clustering of rock wall aspects in the northeastern quadrant. Two of the mostly likely factors are discussed here in greater detail. In the first section a model is constructed which examines variations in solar energy potentially available to model rock walls facing different directions and in clear sky conditions. Values derived from the model are assigned to real rock walls and the influence of this factor on rock wall altitude and development is considered statistically. Secondly, the influence of wind drifting leading to the preferential accumulation of snow in lee concavities is discussed. Correlation and regression analyses are carried out in order (i) to establish whether wind drifting is significant and (ii) to establish the wind direction most likely responsible. Finally, the relative contributions of insolation and lee effects to the clustering of rock wall azimuths are discussed enabling inferences on the climatic environment during periods of rock wall erosion to be made.

The Estimation of Solar Energy Incident at the Surface

The evaluation of solar energy incident on sloping surfaces is required in fields as diverse as architecture, agriculture, forestry and glacial geomorphology (Phillips, 1962; Spencer, 1965; Frank and Lee, 1966; Andrews, 1971). Kondratyev (1969) and Fedorova (1965) determined empirically the effects of slope angle and orientation of the insolated surface on the receipt of direct and diffuse radiation. Equations for computing insolation have been given by Geiger (1969) and Kondratyev (1969) and from these, tables of energy incident at various latitudes and on various slopes have been computed (e.g. Frank and Lee, 1966; Ohmura, 1968). Ohmura's tables for latitude 45^{0}N (the closest latitude given to that of the study area) is reproduced in graph form in Fig. 8.1. This shows the effect on insolation receipt of various slope angles and azimuths in the northern hemisphere. Although gently sloping south-facing slopes receive most energy this is not so on highly inclined slopes. On very steep slopes azimuths close to south receive less energy than those facing east or west since they receive the sun at its highest altitude. This effect would, of course, be least marked at high latitudes.

Although many of the standard equations and tables such as those cited above take into account the effect of the slope itself on the receipt of insolation at points upon its surface they do not consider the shading of that surface from surrounding terrain. In studies of the distribution of cirques, many authors have postulated that shading by the steep headwalls is an important element in the mass balance of cirque glaciers and hence contributes to the process whereby cirques are eroded. Thus, in this study shading by nearby terrain is taken into account in the computation of insolation on model glacier source areas.

The tabulation of the energy that would be received in cloudless conditions on an unshaded surface (i.e. potential insolation) incident on any slope became feasible with the advent of high speed computers. Garnier and Ohmura (1968, 1970) presented one such computational method that permitted the calculation of instantaneous values of direct and diffuse radiation on any slope. They compared this method with empirical measurement in the preparation of insolation maps for

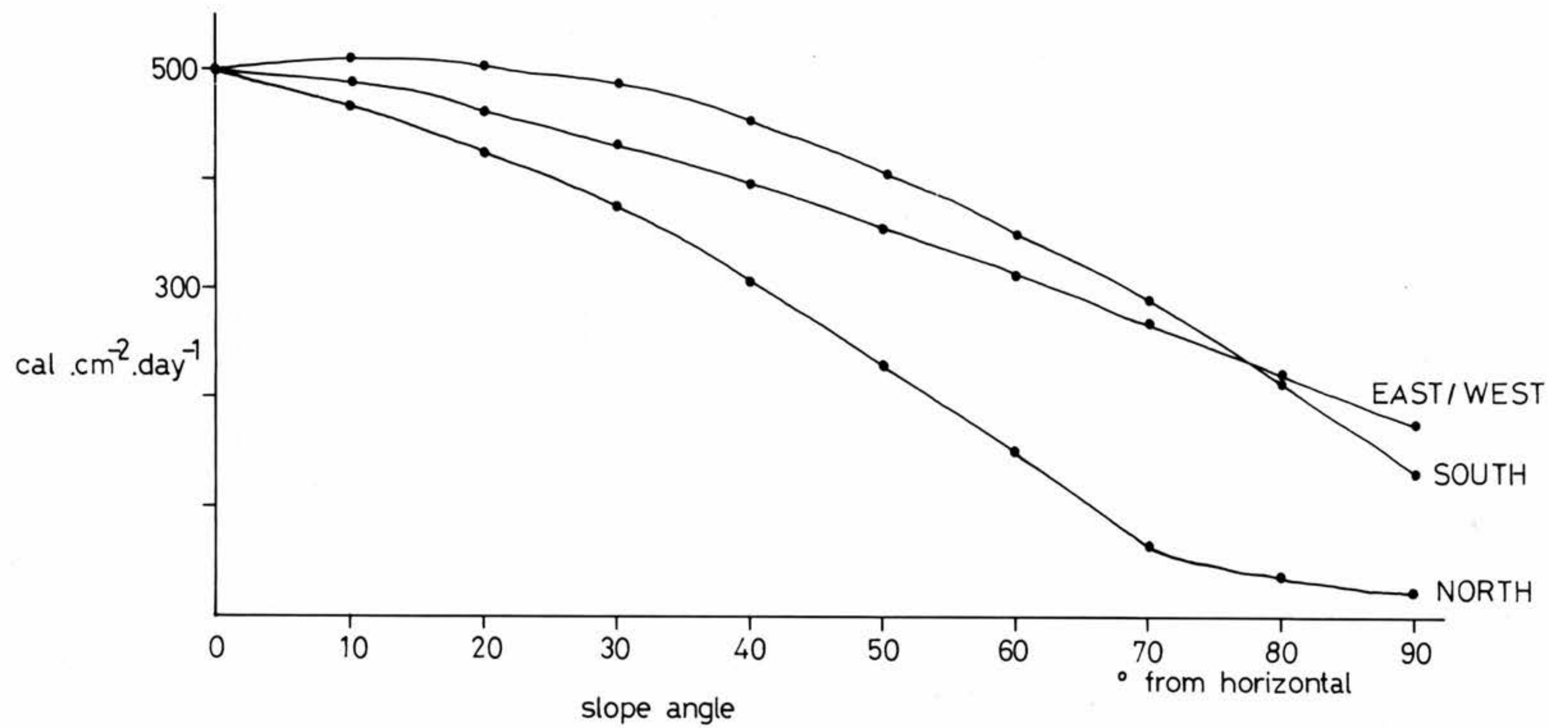


Fig. 8.1 Insolation received on slopes of various aspects and angles

Mont St Hilaire, Quebec. Empirical and computed results were similar under overcast conditions, but less close at other times due to the assumption of an isotropic atmosphere in the estimation of diffuse radiation. However, in clear sky conditions the importance of sky to the total global radiation is least, and it increases towards completely overcast conditions when the atmosphere most closely conforms to the isotropic assumption.

Williams et al. (1971) applied the method to the insolation of large areas including cirques on Baffin Island. Using graph theory, Andrews (1971) and Andrews and Dugdale (1972) had shown that the cirques may be divided into two major groups on the basis of whether or not they are glacierized and it was hypothesised that variations in global radiation receipts are an important explanatory factor (Andrews, 1971). Williams et al. (1971) calculated the amount of global radiation received under clear sky conditions, improving Garnier and Ohmura's (1968) method by taking into account shading by surrounding mountains for large areas. Radiation maps of the area were drawn: the areas receiving least insolation corresponded closely with the glacierized cirques. The fit is not perfect largely because of elevational variations in temperature and the influence of wind drifting on snow accumulation. This approach differed from the present one in terms of scale. In the present study shading by the local rock walls themselves is considered to have the greatest influence on irradiation and the variation in income over short distances from the rock walls is computed. With this approach the influence of rock wall morphology and slope factors may be assessed.

In the last chapter it was shown that the aspects of former glacier source walls in the study area tend to be clustered in the NE quadrant and this was due in part to the effects of solar radiation. Here, a similar method of calculating insolation to those of Garnier and Ohmura (1968) and Williams et al. (1971) is used to assess the significance of insolation to the aspect of glacier source walls. Since the variation in energy receipt is considered to be due to the morphology and orientation of the wall itself rather than to more distant terrain features, a structural model was devised based on the average dimensions of rock walls. This has the advantage that radiation receipts may be mapped for a specific set of locational inputs while all other variables are controlled. The model was used to study how insolation receipt may vary with aspect through shading and slope orientation. Maps of potential clear sky radiation receipt for different orientations, and values of energy received over the whole ablation season were calculated for the study area latitude, the latter being used as a variable in later analysis of rock wall base elevation and amplitude.

The Computation of Insolation Income of a Sloping Surface

The computer program used for the calculation of incident radiation at the surface was developed from a simple one constructed for horizontal surfaces (Brown, pers. comm.) to evaluate the effect of shading of sunlight on the growth of phytoplankton in Loch Lomond. It was altered to take into account sloping surfaces of various angles and azimuths and seasonal variation in turbidity values. A subprogram was written to incorporate the rock wall model.

The total direct and diffuse insolation (global radiation) may be calculated for any point on the earth's surface provided the latitude, date, gradient, and azimuth of the surface are known (Geiger, 1969). The total radiative flux at the edge of the earth's atmosphere is about 1.39 $kW.m^{-2}$ (1.98 $cal.min^{-1}.cm^{-2}$) normal to the solar direction (Allen, 1963). The radiation received by a unit surface outside the atmosphere varies both seasonally and temporally. The eccentricity of the earth's orbit causes variations of about $\pm$ 3.5% during the year (Johnson, 1954). Variations in the obliquity of the ecliptic and the longitude of perihelion are responsible for temporal variations and solar luminosity itself is estimated to vary by a few percent over time (White, 1978). Vernekar (1971) took temporal variations into account in deriving tables and graphs to show the available flux. He followed Milankovitch (1930) in dividing the year into two equal parts such that the heat received during any day in the caloric summer is greater than that received during any day in the caloric winter. For a latitude of 55^{o}N at 10,000 B.P. Vernekar's caloric summer graph shows that just over 4% more energy was available at the edge of the atmosphere than in 1950, although there was nearly 12% less in the caloric winter. This was the greatest annual difference in potential energy over the last 50,000 years (Sissons and Sutherland, 1976). Since there is no way of telling precisely how this variation affected the orientation and slope differences of rock walls eroded over many periods of glaciation the temporal variations in radiation have not been incorporated in the model, present values being used. In any case all these effects are negligible compared to the accuracy of the program and model used.

While traversing the atmosphere the solar flux is attenuated: part of the energy is scattered in the form of diffuse radiation, part is absorbed, and part is transmitted unaltered as direct radiation (Spencer, 1965). Scattering is caused by air molecules, water vapour and dust, part of the scattered portion being redirected and reaching the earth as skylight or diffuse radiation. Most absorption occurs in the upper atmosphere due to the presence of ozone and water vapour.

The attenuation of the direct solar beam depends on the air mass length through which the solar beam passes, this being determined by the altitude of the sun in the sky, and by the absorption properties of the atmosphere. The latter is usually given as the coefficient of absorption per unit air mass, averaged over the whole incident spectrum. The amount of energy attenuated is determined by the transmission factor:

$$T(a_s) = \exp(-m(a_s).\propto) \qquad (8.1)$$

where $m(a_s)$ is the air mass length of the given solar altitude (a_s) and $\propto$ is the absorption coefficent. $\propto$ is composed of losses from the direct flux due to molecular scattering, scattering by the atmospheric particles and absorption (Kondrayev, 1969); it is therefore dependent on the chemical state of the atmosphere.

The air mass length depends on the physical state of the atmosphere, the density distribution of the atmosphere with altitude being most important (Hardie, 1962). For solar altitudes above 30^o from the horizon the atmosphere may be satisfactorily approximated by a horizontally plane-stratified structure (Brown, pers. comm.) such that,

$$m(a_s) = m_{90}.\mathrm{cosec}(a_s), \qquad (8.2)$$

where m_{90} is the air mass at the zenith. For solar altitudes less than 30^o however, this approximation is not satisfactory and the curvature of the atmosphere must be taken into consideration. This may be represented with the necessary accuracy for any solar altitude by a polynomial expansion of $\mathrm{cosec}(a_s)$ (Hardie, 1962),

$$m(a_s) = m_{90} \sum_{n=1}^{N} \mathrm{cosec}^n a_s, \qquad (8.3)$$

where N is the number of terms in the expansion and the coefficients A_n (n=1,N) are chosen to fit atmospheric data obtained by balloon ascent. Hardie (1962) tabulated the coefficient for a sea level site to give the equation subsequently used, as:

$$m(a_s) = m_{90}\, P(\text{cosec } a_s), \qquad (8.4)$$

where,

$$P(\text{cosec } a_s) = \text{cosec } a_s - 0.0018167(\text{cosec } a_s - 1) - 0.002875(\text{cosec } a_s - 1)^2 - 0.0008083(\text{cosec } a_s - 1)^3$$

The full transmission factor equation is thus:

$$T(a_s) = \exp(-\alpha m_{90} P(\text{cosec } a_s)) = (T(90^o))^{P(\text{cosec } a_s)} \qquad (8.5)$$

The coefficient of zenith tranmission $T(90^0) = \exp(-\alpha\, m_{90})$ was empirically derived by Kondratyev (1969) for latitude 54^oN, for the middle day of each month and is given in Table 8.1. This indicates that turbidity is highest in summer, which is due to surface heating and because the percentage of foreign particles washed out of the atmosphere is least in summer. In the high Arctic, Williams <u>et al</u>. (1972) found an annual average transmission factor of 0.6. Sissons and Sutherland (1976) assumed a value of 0.7, similar to present-day Norway, as a summer mean for the eastern Highlands of Scotland during the Loch Lomond Advance. In middle latitudes during clear sky conditions, about 80% of the energy incident at the edge of the atmosphere during the daylight hours reaches the ground (Fritz, 1951) where it is either absorbed or reflected. Here the seasonal variation given in Table 8.1 was used for greater accuracy.

The direct radiation income of a surface which is not perpendicular to the incoming flux is further reduced depending on the angle of the sun relative to the surface. The direct radiative energy flux arriving at a unit horizontal area is therefore

$$S_{hor} = S.\sin a_s.T(a_s), \qquad (8.6)$$

where S_{hor} is the energy flux on a horizontal surface and S is

Table 8.1 Coefficent of Transmission in the atmosphere [1]

Date	Mean Coefficient of Zenith Transmission $T(90^{o})$
January 15	0.8
February 15	0.8
March 15	0.79
April 15	0.78
May 15	0.775
June 15	0.77
July 15	0.76
August 15	0.77
September 15	0.785
October 15	0.795
November 15	0.805
December 15	0.81

Notes (1) Kondratyev (1969) for latitude 54°N

the solar flux at the edge of the atmosphere. Kondratyev (1969) reviewed the Russian literature concerning the receipt of solar radiation on sloping surfaces. He showed that the flux arriving at a sloping surface is related to the difference between the solar azimuth and the azimuth normal to the ground surface, and to the gradient of the surface, giving

$$S_{sl} = S.\cos i.T(a_s) \qquad (8.7)$$

where i is the angle of incidence of the sun's rays to the normal to the surface, found using the spherical equivalent of the plane Euclidean space cosine rule (Smart, 1962):

$$\cos i = \sin a_g.\sin a_s + \cos a_g.\cos a_s - \cos d_{az} \qquad (8.8)$$

Here, a_g is the ground slope subtracted from 90^o (i.e. a_g is the astronomical altitude of the surface normal direction), and d_{az} is the difference between the astronomical azimuth of the normal to the ground plane and the azimuth of the sun. With basic inputs of latitude, date, ground slope and azimuth, the total instantaneous direct radiation at the surface may be calculated.

Diffuse radiation is that part of the solar beam which is scattered in the atmosphere but re-directed towards the surface, arriving from all directions. Geiger (1969) reported work of Kondratyev and Manolova that showed that for slopes up to an angle of 30^{o}, the sky radiation can be regarded as independent of azimuth and thus affects equally slopes oriented in all directions. However, as a proportion of total radiation received it is much more important on north-facing slopes than on south-facing, particularly in winter. The amount of scattered light varies with atmospheric conditions even with cloudless skies, the total scattered skylight incident on a horizontal surface varying by a factor of 3 about a mean fraction of the order of 0.2 of the direct flux (Kondratyev, 1969). This fraction does not vary over a wide range of solar altitudes but is of course much higher for cloudy days. If an isotropic atmosphere (one in which all parts of the sky contribute equally to the diffuse flux) is assumed, the total amount of diffuse radiation reaching the ground depends on the amount of sky not obscured by surrounding topography. In this case the flux of scattered light through a horizontal unit area may be written as

$$S_{dif} = S_{hor} . \sigma(1-\Psi) \qquad (8.9)$$

(Kondratyev, 1969), where Ψ is here taken to be 0.2 and σ is the fraction of the sky obscured by the surrounding topography, and $S_{hor}(a_o)$ is the value for the solar altitude in the absence of interference by the topography.

Williams et al. (1972) incorporated a theoretical equation for diffuse radiation on sloping surfaces assuming isotropic conditions. This has not been done here since interest is centred on the relative spatial variations in radiation receipt rather than the actual amounts, and the diffuse component of radiation varies with slope orientation in the same way as the direct flux.

Daily totals of solar energy receipt may be obtained by integrating Equation (8.7) over the period from sunrise to sunset. For a plane surface where the actual horizon is the same as the true one the length of time that the direct solar illumination takes place may be found from tables (given, for example, in List (1952)). However, this is of little use here. Rock walls by their very nature may cut out the sun to the glacier below, casting a shadow at various times of the day. For there to be no shadow at a given point, at a certain time during the day, the solar altitude must be greater than the angle subtended by the point to the point on the rock wall crest that coincides with the solar azimuth. The relation of the altitude of the sun to the local horizon thus depends on the topographic model of the wall chosen.

The rock wall model used in this study has been chosen so that it is an average shape that has dimensions that are common in the study area. The model consists of walls, semi-circular in plan view, with a flat apron or floor in front. The semi-circle is not unrepresentative: in the homogeneous rock of the Cairngorms, this is the most common form of both rock walls and cirques (Sugden, 1969). The rock wall is represented by a uniformly sloping surface at an angle of 38^{0} to the horizontal. An amplitude of 150m was taken, thus forming a model rock wall of width 190m and crest length just greater than 1000m. The structure is drawn in Fig. 8.2.

Andrews and Dugdale (1971) constructed a model cirque for Okoa Bay, Baffin Island in order to understand the significance of insolation in the present distribution of glacierized

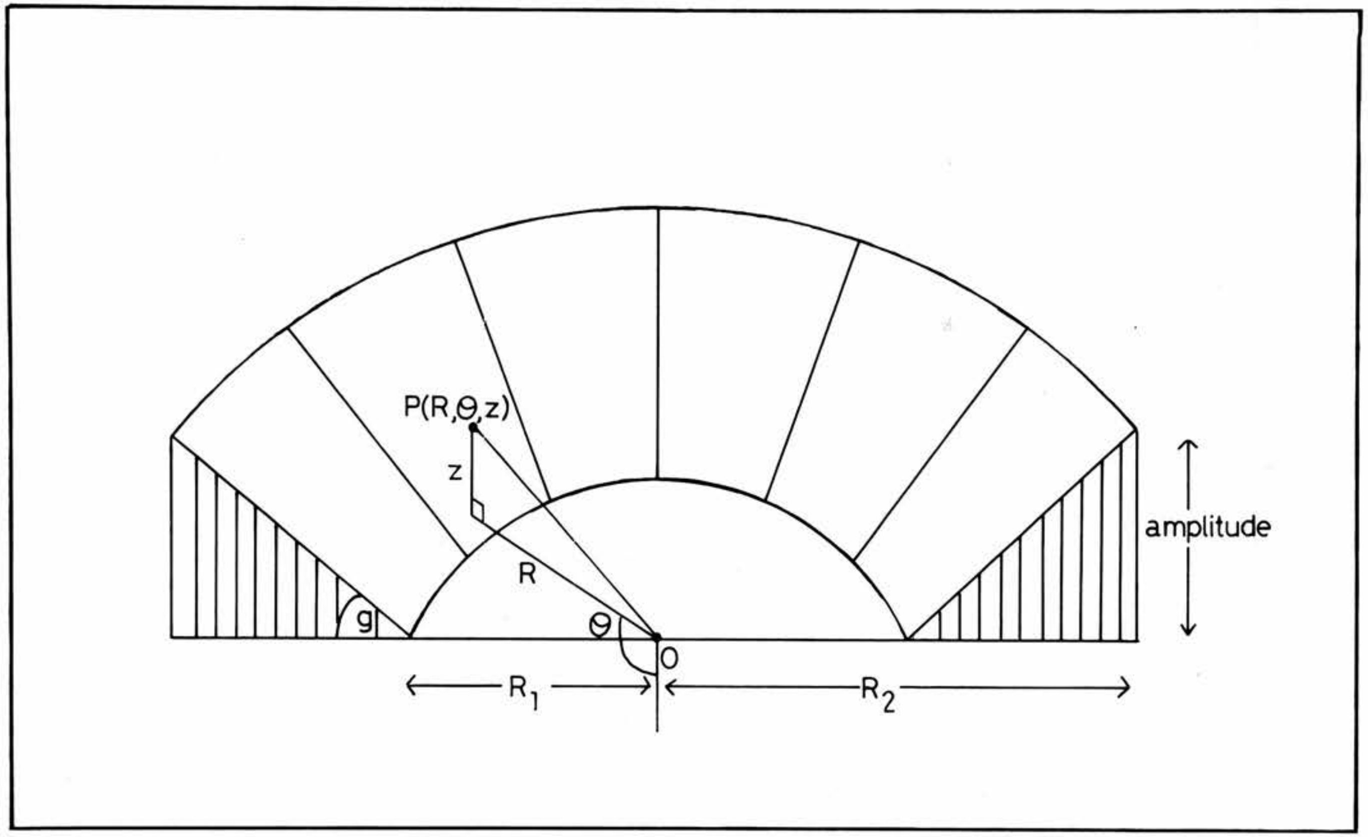


Fig. 8.2 Rock Wall Model used for insolation calculations

cirques. They also constructed their model from median values of morphometric variables they measured on the cirques. They chose an angle of 36^{o} between the mid-point of the cirque and the mountain summit, the actual slope comprising a gentle floor zone slope, steep cliff section and a gentle slope from crest to the mountain summit. The plane shape was a semi-circular headwall, elongated down slope to an outlet with an amplitude of 257m from crest mid-point to the cirque mid-point, although their diagram does not conform to this. The location was $67^{o}30'$N. Orientating this model to face north or south, the daily sun-path relative to the local headwall horizon was derived using standard tables. Thus for the model oriented northwards the midday sun is over the horizon for 51 days of the year, the maximum altitude it reaches being 10^{o}. However, for the same shape model facing south, an incipient glacier would be exposed to the midday sun for the entire ablation season of about twice this period. Andrews and Dugdale (1971) concluded that the present distribution of glaciers is a result of variations in the solar radiation received between different slope aspects with possible enhancement by variations in the distribution of precipitation.

Calculation of Daily Direct Radiation on the Model Rock Wall

For any point within the confines of the model rock wall the daily direct insolation may be calculated taking into account shading by the surrounding topography and the slope exposure and angle. An advantage of the semi-circular model plan is that any point on the wall or apron may be given a unique set of polar cylindral coordinates $P(R,\Theta,z)$ where R represents the distance between P and the centre of the coordinate system. Θ describes the angular distance from the rock wall mid-point azimuth to the radius vector R and z is the height of P above the model floor.

The morphology of the model and its aspect determine whether the sun is above the local horizon at any time. Using solar altitude and azimuth tables in List (1952, p.496) sun-path diagrams over the local horizon have been drawn for the model structure facing north and south for the 22nd June (Fig. 8.3). The sun reaches a maximum altitude above the true horizon of 32.5^{o} at the summer solstice, in a north-facing rock wall at a latitude of 57^{o}N. For the same structure facing south it reaches 56^{o} above the horizontal surface. The length of time the two surfaces are illuminated also varies, particularly at the beginning and end of the ablation season: on April 16th and August 28th the north-facing rock wall many only receive energy for some 7 hours, whereas the south-facing equivalent is illuminated for 12 hours.

In order to establish if the sun is above the horizon for a point P at a given time, the angle subtended from that point to the crest where it coincides with the solar azimuth is compared to the altitude of the sun when at that azimuth. If the astronomical altitude of the rock wall seen from P is larger than the solar altitude the sun is above the horizon and the solar flux arriving at the surface is calculated. Otherwise insolation is set to zero for that time interval. Obviously, the next task is to integrate this over the period from true sunrise to sunset to find the daily flux. Since the local horizon arrangement may be such that the sun 'rises' and 'sets' more than once in the diurnal cycle integration by calculus cannot proceed. Instead a method of testing the difference between the solar and ground altitudes over discrete time intervals has to be used, aggregating the flux over these periods. In a previous study of insolation reaching a horizontal surface Brown (pers. comm.) considered that a sampling angle of 5^{o} throughout the 360^{o} day (equivalent to descrete time periods of 20 minutes) was sufficiently detailed to define the daily variation of the radiation income. The

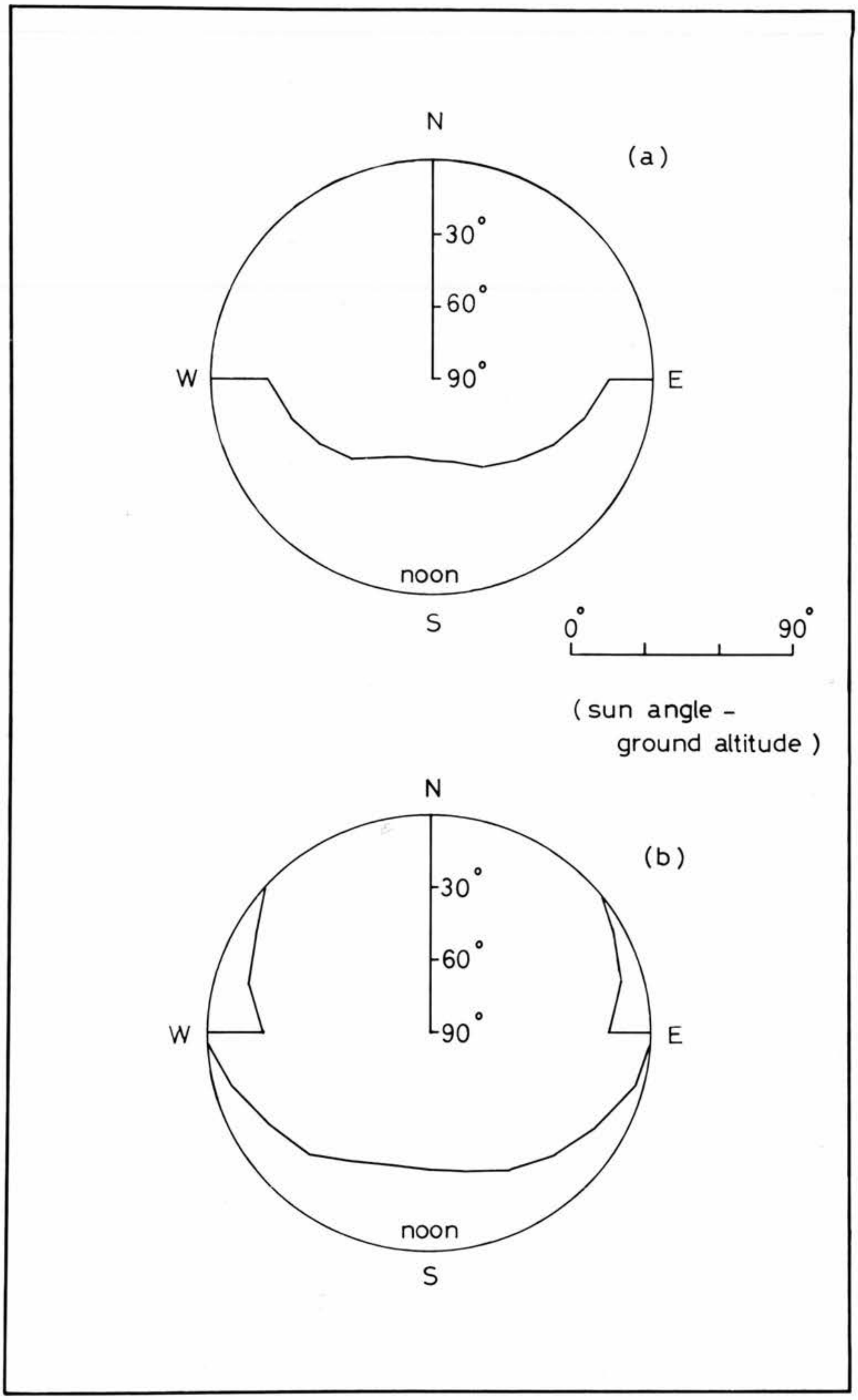


Fig. 8.3 Sun-path diagrams for rock wall model, June 22
(a) South-facing (b) North-facing

problem of arriving at a sufficiently accurate sampling design was discussed by Ohmura (1968) who concluded that the difference in accuracy between a sampling interval of 20 minutes and 1 minute was less than 5%. The saving in computational time with the former are enormous.

The altitude of the sun is calculated by the formula given in Smart (1962):

$$\sin a_s = \sin \varnothing . \sin \delta + \cos \varnothing \cos \delta . \cos h \qquad (8.10)$$

for the middle part of each time period, where $\varnothing$ is the latitude, δ is the solar declination, h is the solar hour angle measured from midday and a_g is the ground altitude. Because each point suffers different shading conditions throughout the day, to study the insolation of the rock wall and apron as a whole, points on a predefined grid are evaluated using the program, and their values are summed. Using simple trigonmetry and with angles in radians (referring to Fig. 8.4):

$$HA_{PS} = \tan^{-1}\left(\frac{ZS'}{PS'}\right) , \qquad (8.11)$$

where S' is the point on the horizontal plane through P perpendicular to S. The altitude of the crest is simply

$$ZS = z_s - z_p , \qquad (8.12)$$

where z_s and z_p are repectively the altitudes of S and P above the apron.

$$PS' = R_2^2 + R^2 - 2R_2R \cos (\Xi) \qquad (8.13)$$

where $$\Xi = \sin^{-1}\left(\frac{R}{R_2} \sin \Omega\right) - \Omega ,$$

and $$\Omega = \pi - \Theta + AC - A$$

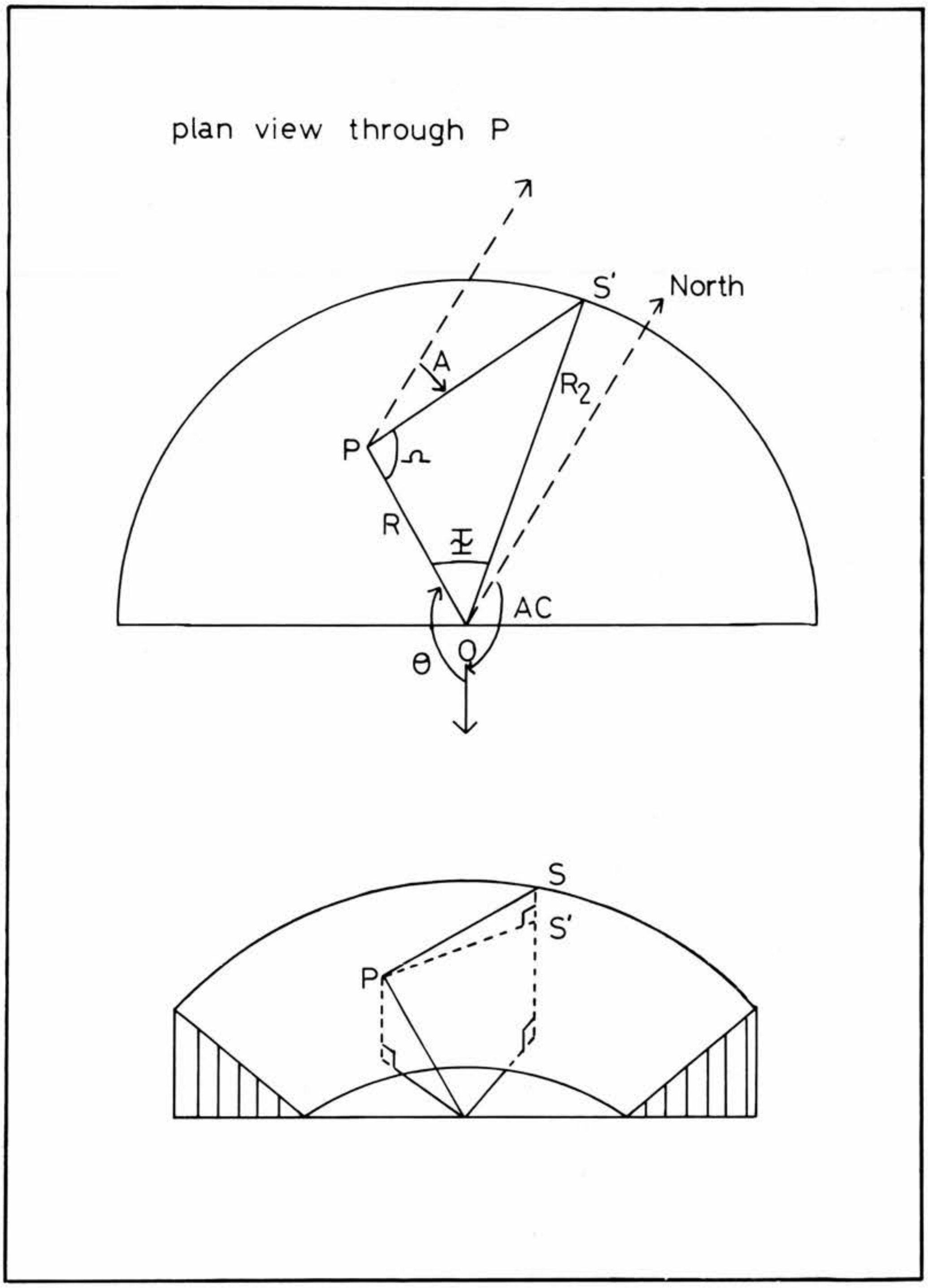


Fig. 8.4 Method of calculation of insolation received on rock wall model

is used to related the internal framework of triangle PS'O to the solar azimuth, while A is measured away from north in 20 minute (5^{0}) intervals. Thus by increasing A by 5^{0} from 5^{0} to 360^{0} the angle subtended by P to points along the crest is calculated and coincides with the calculation of the solar altitude in Eqn (8.10). If the value obtained from Eqn (8.11) is greater than that from (8.10) the sun is considered to be above the horizon for a full 20 minutes. However, the amount of direct insolation arriving at P is only calculated for that period if the solar altitude is 2^{0} greater than the ground altitude. In this manner summation is carried out over the whole day using Eqns (8.7) and (8.8). With the basic morphometric inputs of crest length, amplitude and gradient derived empircally and with the date, latitude and transmission factor, the maximum amount of direct solar radiation arriving at the surface may be computed. A FORTRAN computer program was written for this purpose, the basic equations for solar flux arriving at a horizontal surface being given in a program originally written by Dr J. Brown and the rest developed by the current author with his help. The full program is listed in Appendix 3.

The program was used to find values of S_{sl} for points within the model framework for various rock wall mid-point orientations. Obviously, interest is not in instantaneous values, or even in daily totals, but in variations over the whole ablation season. Since concern is purely with direct insolation, and this latitude (taken as 57^{0}N throughout) potentially receives 85% of its possible direct insolation between the months of April and September, these six months were taken as the period of interest in insolation. The winter half year was not considered. This may well be too long a period in view of the lag of temperature particularly at the beginning of this period, another short-coming being that the insolation season is longer on south-facing slopes than north-facing.

Nonetheless, to get average values and azimuthal comparisons, the total amount of insolation received at the intersections of a net of points within the model rock wall was aggregated over the period from April to September, calculating the input on the middle day of each month. The net of coordinates (R, Θ, z) covered the rock wall and apron with 180 points P, and for each of these the seasonal potential for direct solar energy was calculated. Each point $P(R, \Theta, z)$ was assumed to be representative of its local area and the model was divided into segments, lines drawn so that each spot was represented by its closest $P(R, \Theta, z)$ point. The areas circumscribed by these lines were calculated and the potential total rock wall insolation computed. From this a mean value for the wall was obtained. Hence a wall may be characterised by one quantity: the potential amount of direct radiation falling on a square centimetre averaged over the wall and the whole insolation season, the units being $cal.cm^{-2}.day^{-1}$.

Maps showing the distribution over the wall of insolation received (i.e. averaged over the insolation season) were produced for the mid-point orientations corresponding with the measurement classes of orientation used in the morphometric study. Maps of the percentage variation in the amount of energy received over the period from April to September between horizontal surfaces with no shading and the rock wall model oriented north and south were produced (Fig. 8.5). The horizontal surface receives $92.7kcal.cm^{-2}$. The apron of a north-facing rock wall receives 90% of that incident on a horizontal surface while 30% is received on the wall close to the base of the wall itself. The reasons for the reductions are twofold: firstly, the whole wall receives less insolation because of the surrounding topography, the losses being greatest at the base of the wall; secondly, the wall slopes northwards, thus decreasing the amount received relative to a horizontal surface of one perpendicular to the flux, since the rays are

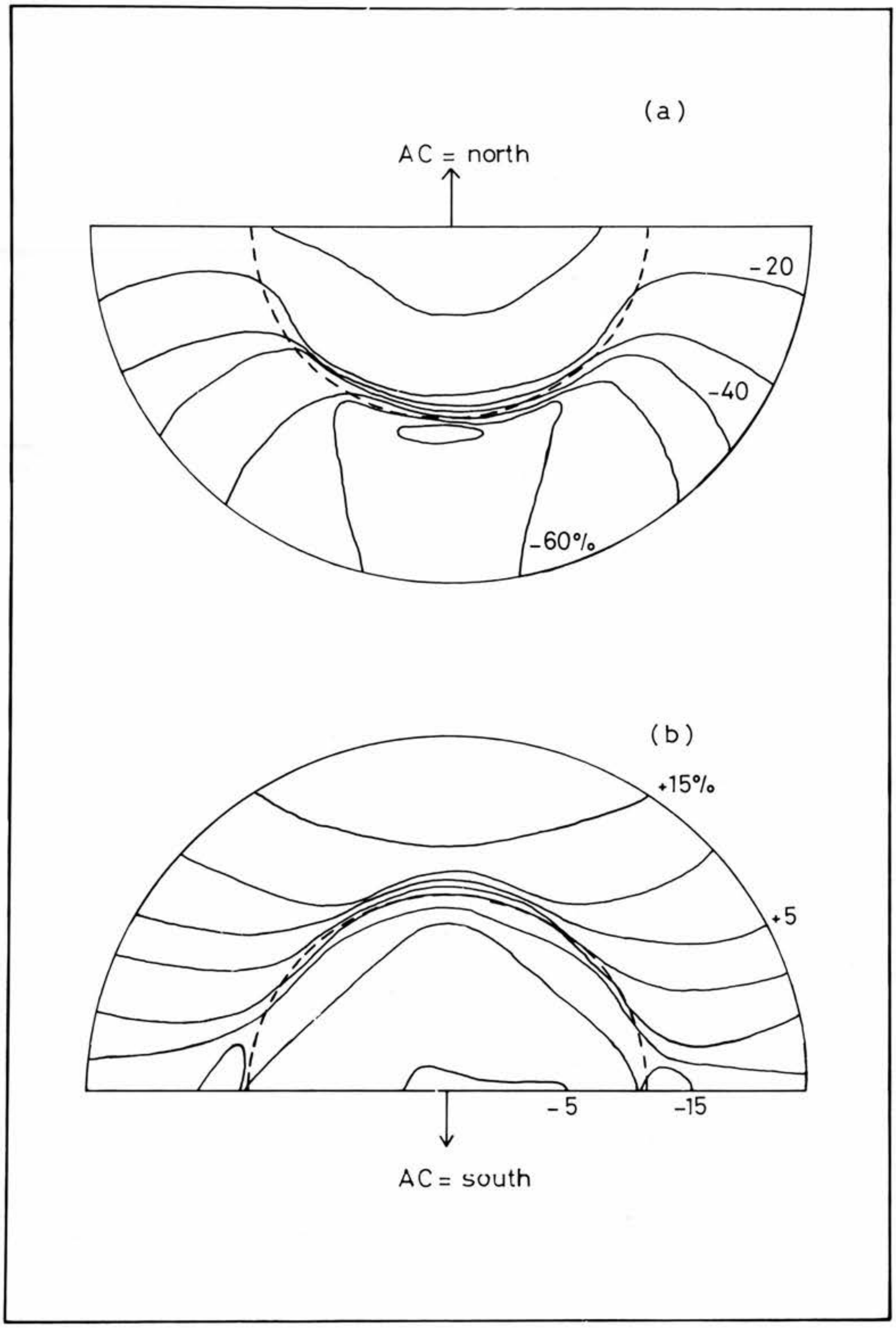


Fig. 8.5 Receipt of Direct Insolation as a % of that incident on a horizontal surface, April - September, 57°N (a - north-facing, b - south-facing)

spread over a wider area on reaching the Earth's surface. The south-facing slope receives between 95% and 115% of that received on a horizontal surface. The decrease is due to some shading of the surface by the surrounding topography, but since the slope is tending to bring the rock wall surface towards a position perpendicular to the flux, this slope receives more than the horizontal, the greatest shading again occurring at the centre of the rock wall base.

These two diagrams indicate the potential variation in insolation protection afforded to glaciers adjacent to rock walls of the same dimensions but different orientations. Five maps of potential energy receipt were produced since corresponding east and west slopes have the same characteristics under clear skies and with no diurnal variations in transmission. These maps are produced in Fig. 8.6. As the rock wall mid-point aspect is rotated from north through east to south, so the area that receives least insolation follows. The least energy is received near the base of the rock wall and always below that point that faces the north. Values of energy potentially available vary from a maximum of over 110 $kcal.cm^{-2}$ on directly south-facing slopes to a minimum of less than $30kcal.cm^{-2}$. On the surface of an incipient glacier sloping across the apron, there appears to be little difference in energy received between the orientations in terms of shadow from the rock walls. Over $80kcal.cm^{-2}$ are received by most of the floor area of each rock wall, and this would be increased with a decrease in altitude difference between the glacier surface and crest. The only difference would be in surface slope direction and as this model shows, the surface slope and its aspect are particularly important factors in the energy received.

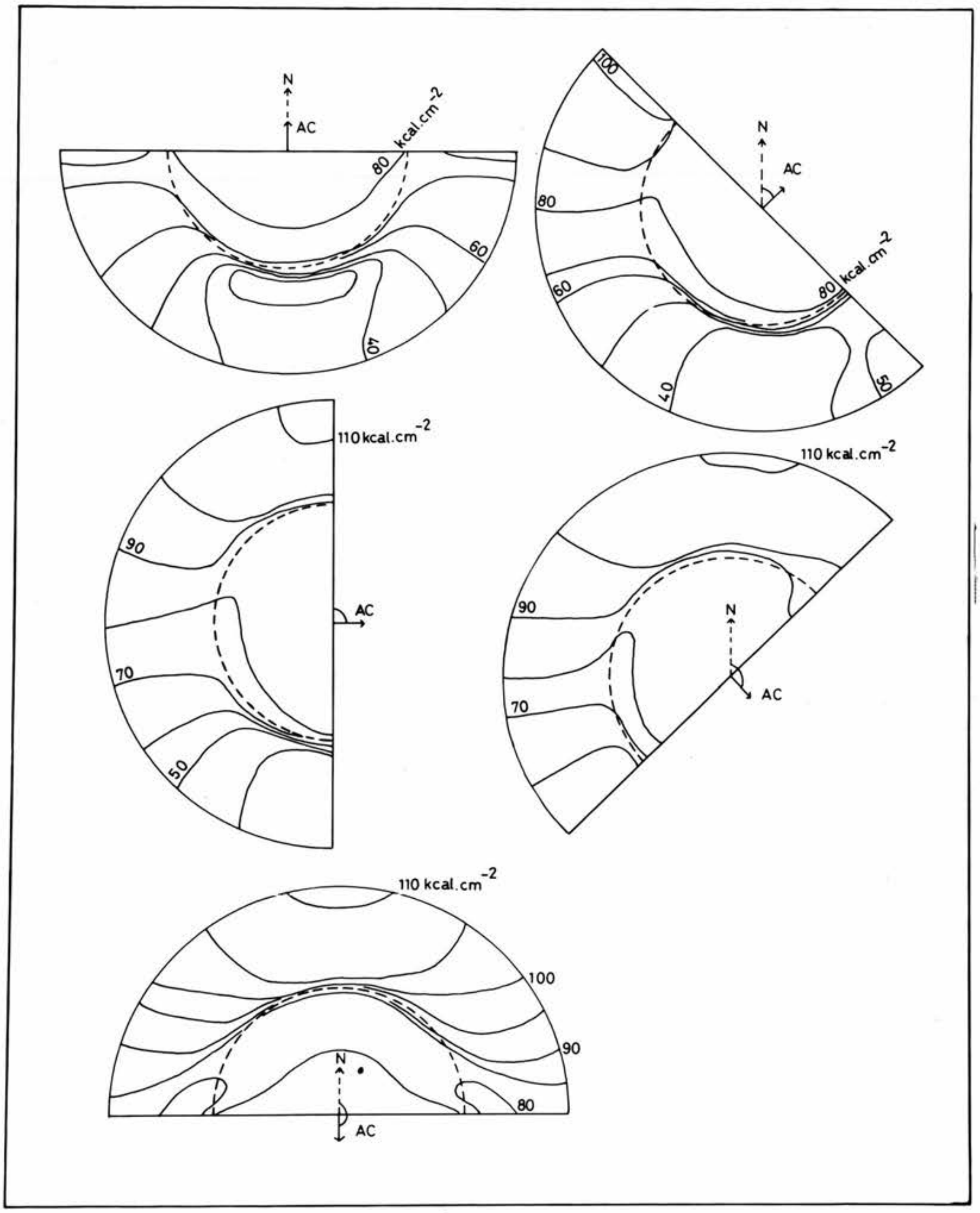


Fig. 8.6 Potential solar energy incident during the summer half-year (April - September), for various mid-point aspects

The actual potential energy that may be lost to the surface through shading may be considered using the model. In the literature there is argument as to the importance of shading in the siting of cirque glaciers. Embleton and King (1975, p.225) suggested that shade is the most important factor in the aspect of cirques. Williams (1972) found that shading of topography influenced the state of glacierization of cirques in part of Baffin Island. His computer program for calculating the direct radiation received by a cirque accounting for shading was used by Andrews et al. (1970) in Baffin Island. They found large differences in direct radiation received by glacierized, partly glacierized and empty cirques.

On the other hand, while dealing with the location and altitude of glaciers belonging to the Loch Lomond Advance in the SE Grampians, Sissons and Sutherland (1976) discounted shading because of the relatively low latitude, the low amplitude of relief in the area, and the outward sloping nature of the former glaciers, which would cause reflectance from their northerly and easterly sloping surfaces, even if the walls provided no shade. These arguments are valid in the particular case of equilibrium conditions that they were considering. However, the importance of the initial location of glaciers beneath rock walls under marginal conditions is different. At this time the shading by walls is at its most extreme and the combined effects of slope and shade may be considerable. Fig. 8.6 showed that at the base of the rock wall there is a large decrease in insolation received compared with the horizontal surface with no shading and the difference is maximised for rock walls with a northerly aspect.

The influence of shading alone may be computed by setting the ground altitude input to 90^{o} (90^{o} minus the surface slope of 0^{o}) but leaving the surface shape the same. Fig. 8.7 shows the result for a NE-facing rock wall. If this were a rock

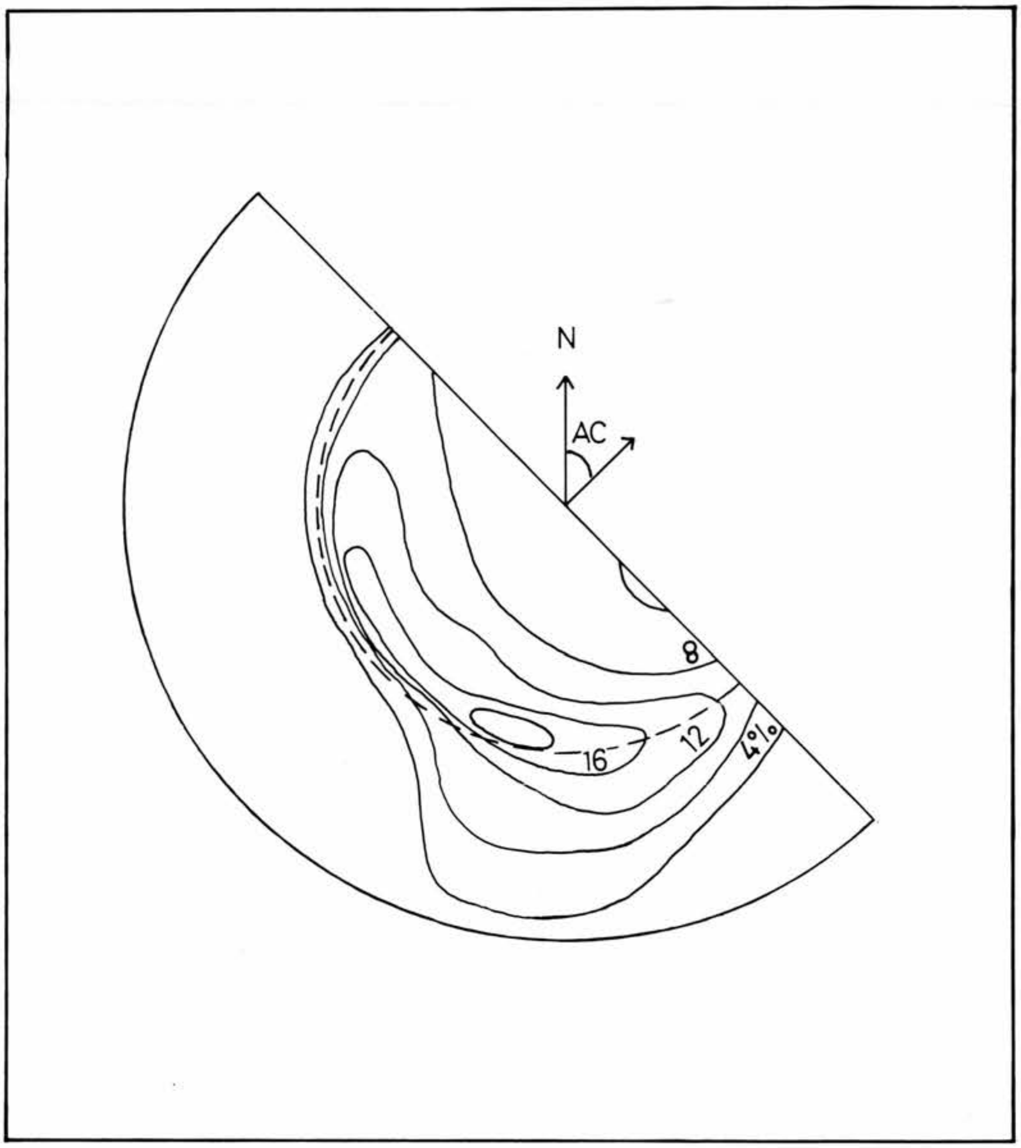


Fig. 8.7 Loss of the Direct Radiative Flux through shading by Topography

wall perched on a valley side the influence of shading would be virtually nil some 150-200m out from the base of the wall. However, for a rock wall glacier at, say, the head of a valley with steep side walls as well as a headwall, a minimum of some 4-8% of potential energy would be lost even on the most favourable parts of the glacier surface. Nevertheless, the model suggests that generally the initial surface slope and aspect are of greater overall importance than the local effect of shading.

The influence of solar radiation on a small steep north-facing rock wall glacier (if the environment is marginally suited to glaciation) is indicated by the model to be such that short glaciers are produced that cannot expand far from their source wall protected areas, since increase in length would mean a decrease of surface slope and an ablation area less protected from heating due to the protection afforded by shading. Loch Lomond Advance glacier limits mapped in the Cairngorms (Sissons, 1979b), an area for which the evidence suggests precipitation was low at that time (Sissons, 1979a; Birks and Mathewes, 1978), show that several of the north-facing glaciers lying beneath rock walls were restricted to limits close to their source walls. The conditions for glacierization at this time may have been similar to those suggested by Graf (1976, p.80) who envisaged that 'the cirque, originally a form produced by the process of glaciation has become a form that controls the glacial process'.

The model values were compared with the insolation section of the program run using a real rock wall. For this trial, Coire an Lochain in the Cairngorms was chosen. This is a north-facing rock wall on the north side of the Cairngorm plateau, almost semi-circular in plan and with a lochan below. Having placed a transect of points on the 1:25000 map using a 100m spacing along the longitudinal axis, the angle subtended from each point with the crest at 5^0 intervals about the summit was calculated, and this, subtracted from 90^0, was entered in the program as the ground altitude along with the slope angle and azimuth at each intersection. The other inputs (latitude, transmission factor) were as before. The result was a range of values for the insolation season from a potential of $31kcal.cm^{-2}$ to $90kcal.cm^{-2}$, indicating close similarity with the north-facing model. The centre line profile of insolation is shown in Fig. 8.8. Again the decrease in insolation is only marked and rapid close to the back wall slope where the floor angle rises.

The Influence of Insolation on the Location of Rock Walls

So far the potential insolation model has shown that at this latitude and with the rock wall dimensions common in the field area insolation need not vary greatly between azimuths and in its distribution within the structure except close to the rock wall base. The insolation model may also be used to attempt to explain the altitudinal location of rock walls in the study area as well as to give an indication of the topographic effects of rock walls on the potential energy received at the surface. In order to do this an insolation coefficient that characterises the rock wall was calculated giving a mean potential for the insolation season for various rock wall aspects. The insolation coefficient was defined as the potential direct insolation per unit area per day for a given aspect. Each rock wall was assigned a coefficent based on its mid-point aspect and the results are given in Table 8.2. The slight differences between east- and west-facing slopes is due to the discretization used in the program. The south-facing rock wall has an energy potential over 60% greater than the north-facing slope.

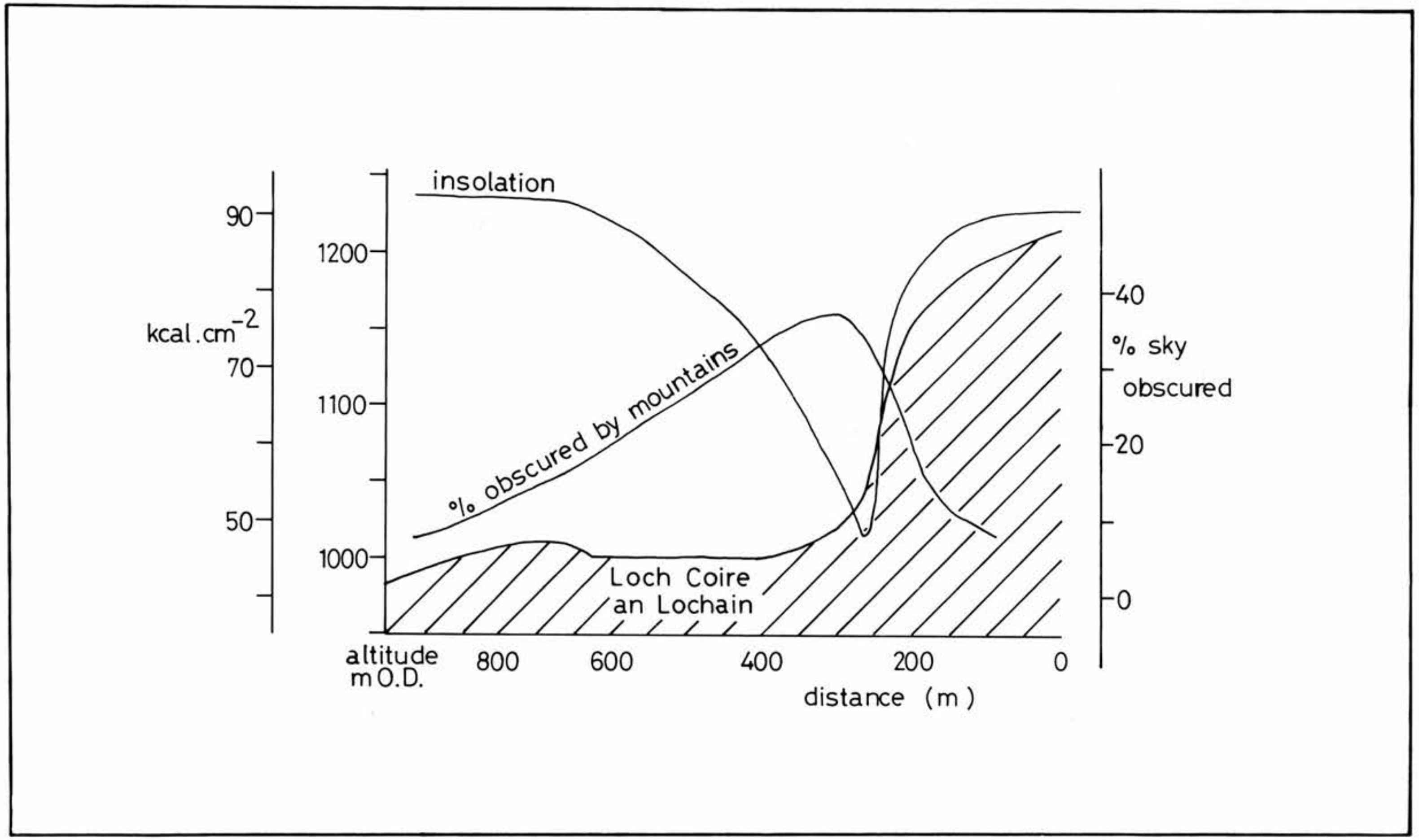


Fig. 8.8 The Direct Radiative Flux, Coire an Lochain, Cairngorms

Table 8.2 Mean Values of Direct Insolation received during the Summer Season

Aspect	Energy (cal.cm^{-2}.min^{-1})
North	320
North-east	354
East	428
South-east	498
South	523
South-west	498
West	429
North-west	352

In the last chapter no clear relationship between rock wall altitude and aspect was found, it was inferred that this was due in part to the interference by external ice masses over-running sites only suitable when the climate had deteriorated greatly. These sites may be at low altitudes or in unfavourable apects.

It might still be expected that the residual values from any trend surface of rock wall altitudes would show a relationship with aspect, such that rock walls greatly above the trend would tend to face unfavourable aspects while those well below the trend would tend to occupy favourable aspects. In Fig. 8.9 the residuals from the SE Grampians and Cairngorms cubic trend surface were plotted against aspect (this area displaying the greatest variety in aspect and the least spatially clustered trend). The NE quadrant contains the widest spread of residual values and contains almost all the high negative residuals. Those in the NW and SW quadrants are generally above the trend.

It is hypothesised that, *ceteris paribus*, the clearest relationship between aspect, in terms of insolation, and altitude, should be found where the regional altitudinal trend is eliminated and the influence of ice external to individual potential source areas is minimal. This was tested in part of Skye.

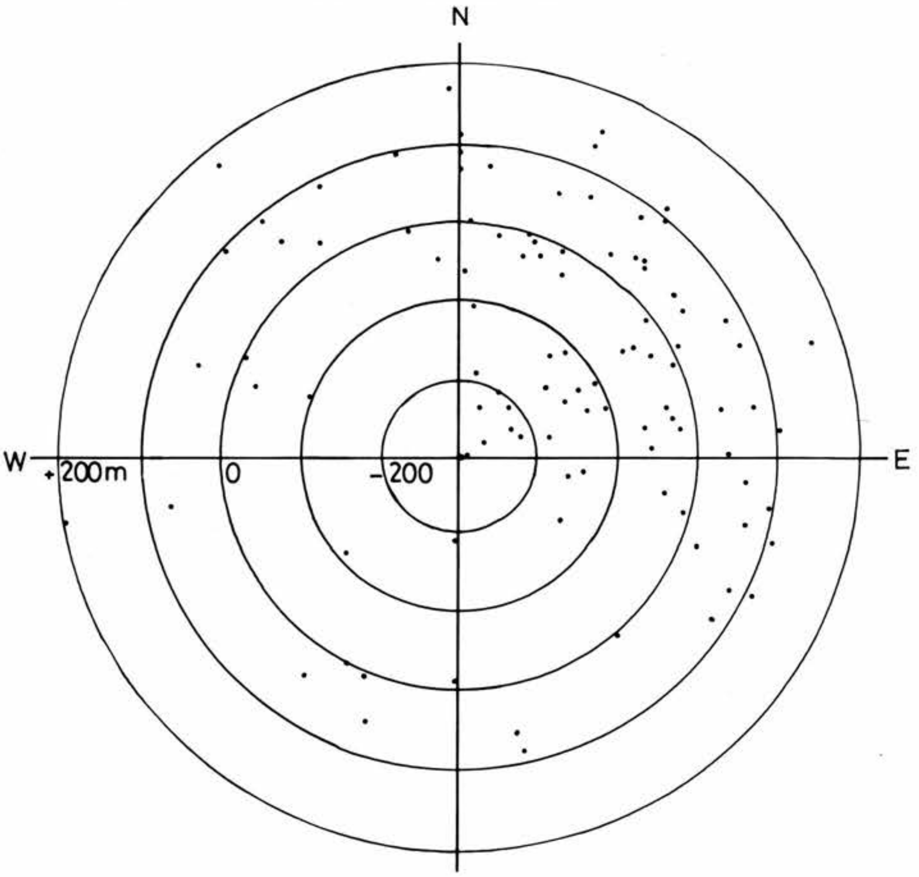


Fig. 8.9 Rock Wall Asbect and Residual Altitude from Cubic Trend surface, SE Grampians and Cairngorms

The outer edge of the Cuillin ridge on Skye represents a unique area of rock wall formation in the study area for several reasons: (1) the summit altitude along the ridge varies little; (2) rock wall formation has been least interrupted by ice-sheet action; (3) there are rock walls facing in every direction; (4) the knife edge ridge excludes the complication of snow blowing off plateaux; (5) there is no regional locational trend in rock wall altitudes; and (6) the rock walls radiate from the ridge crest so that there is no coalescence of headwalls as in the interior of the ridge along the SW side of the Coriusk valley. These factors imply that rock wall base altitudes are minimally affected by most factors that tend to vary the altitude of rock walls regionally and locally. For the 20 rock walls on the outside of the Cuillin ridge the rock wall base altitude was regressed against the insolation coefficient. The simple correlation of 0.2628 was obtained which is not significant at the 0.1 probability level. Allowing that location on the ridge may be of some importance the partial correlation coefficient between insolation and rock wall altitude controlling for site location in terms of easting and northing was calculated, giving a value of 0.4001, which is just significant at this level. This analysis indicates that expressed in this way the potential direct insolation is a marginally significant influence on the altitude of rock walls in the Cuillins.

The above set of tests was also carried out using the square root of amplitude as the independent variable. Although a partial correlation coefficient between amplitude and the insolation coefficient of -0.3796 was obtained, this was not significant at the 0.1 level. The negative sign of the coefficient suggests however, as would be expected that insolation and rock wall amplitude are to some extent inversely related.

There are two possible sets of reasons why the correlations between altitude and amplitude and insolation are not greater. The first set concerns the drawbacks of the model itself, and the second concerns the climate during glaciation.

The insolation model is a crude tool for estimating, even qualitatively, variations in the absorption by a glacier of energy available to it. Only direct radiation values have been calculated, these representing the greatest possible differences in energy available at the surface. However, distinctions between slopes are diminished if diffuse light from a cloudy sky is taken into account, although this energy input does not itself vary between slopes. Collingbourne (1976) showed that in Great Britain at present diffuse radiation may represent 80% of the total radiation received in winter and around 60% in summer, and as the diffuse proportion increases, the variation between slopes diminishes. The introduction of clouds and water vapour in the atmosphere decreases the relative importance of direct insolation and hence decreases the variability between slopes of different aspects.

A second factor is that temperature and ablation are controlled by the amounts of energy absorbed by a glacier surface rather than by that incident on the surface. This is strongly dependent on the surface reflecting characteristics, the albedo. Kondratyev (1969, p.425) states that the albedo of snow varies from 100% for dry snow to only 20-30% for dirty moist snow, and that during a spring thaw albedo may drop to around 20%. Similarly, Tronov (1962) reported how summer snowfalls greatly increase the glacier albedo and reduce ablation. Albedo also varies diurnally because of its dependence on solar altitude relative to the ground slope. Further, a south-facing glacier not only receives more energy during the sunlight hours, but the absorbed energy has a positive feed-back effect of reducing the albedo through surface thaw and thus increasing the amount of energy that may be absorbed. Therefore the daily differences between north- and south-facing slopes is increased. The addition of an albedo factor to the insolation model would have enhanced slope azimuth differences proportionally (while decreasing the actual values for each azimuth).

A third factor is the importance of air temperature rather than incident radiation in the melting of snow and ice. To allow for the lag between diurnal insolation maximum and temperature maximum, the values in Table 8.2 were replaced by those representative of the solar radiation two hours previously. This was done by plotting the values in the table as a line graph and interpolating to obtain the value related to an aspect 30^{0} around, moving anticlockwise. The multiple regression analyses described above were carried out again, the correlation coefficient between rock wall base altitude and potential insolation increasing from 0.2628 to 0.3896, which is significant at the 0.1 level, although not at 0.05. The partial correlation coefficient between altitude and insolation, while controlling for location, is 0.6753, which is significant at the 0.01 level. The similar partial correlation coefficient between amplitude and insolation is -0.4608, significant at the 0.1 level. These results indicate the importance of the time lag effect between insolation and the temperature and in fact indicate that insolation receipt is a highly significant variable in the development of rock walls.

The second set of reasons for the apparent lack of a relationship between rock wall altitude and amplitude and the insolation model concerns the climate during periods of rock wall formation. In earlier chapters it was inferred from the distribution and altitude of rock walls in the field area that in winter precipitation was very high particularly in west coast locations such as this. In summer however, it was inferred that precipitation, falling as rain, was less. Provided the insolation values calculated here reflect real differences in energy received, the results of the regression and correlation tests agree with the summer inferences. Since insolation is a significant factor in rock wall altitudes, it may by inferred that in the ablation season there were frequent periods of clear skies and sunshine.

The above results indicate that the insolation model is an effective, although a crude tool for measuring the effects insolation on the choice of sites for rock wall glaciers. The incorporation of albedo and diffuse radiation to the model would lead to greater accuracy in the computation of the actual quantity of radiation available for ablation. Both initially appear to enhance the differences between slopes and azimuths. However, where diffuse radiation forms the greater part of global radiation, differences in receipts on north- and south-facing slopes are decreased and protection from insolation need not be a significant factor in glacier mass balance and hence location.

The Redistribution of Snow by Drifting

In Chapter 6 a definite trend (rising inland from the west coast, and with a northwestward rise superimposed in the east from) was found in the base altitude of rock walls. It was hypothesised that this is related to the broad scale trend in precipitation received across the field area. At a more local scale on individual mountains it is uncertain whether the lee or windward slope receives more direct precipitation, but where solid precipitation is concerned the transference of snow from upland areas into lee slope locations during snowfall and immediately after by wind drifting is important. The locations of rock walls in areas with extensive plateaux may therefore indicate the general wind direction during the accumulation of snow when the rock walls were being formed.

The regional map of rock walls in the Cairngorms (Fig. 3.6) indicates the locational relationship between rock walls and large tracts of high plateau, the walls lying on the northern and eastern sides of the high ground. This suggests that there may be a functional relationship between the siting of accumulation areas and the existence of large areas from which blown snow could potentially be accumulated. The relationship is not applicable throughout the field area, however: in Skye and Rhum, for example, plateaux are of limited extent (Fig. 3.3). On Skye the best-developed rock walls are located on either side of the knife edge Cuillins ridge, and face in various directions.

Sissons (1977,1979a) has interpreted the azimuthal and volumetric distribution of Loch Lomond Advance glaciers largely as a response to snowfall associated with warm and occluded fronts embedded in southwesterly airstreams which give rise to south and SE winds. At present depressions commonly pass SW-NE along tracks to the north of Scotland having originated in the boundary between tropical and polar air masses in the North Atlantic between Newfoundland, Iceland and N. Norway (Manley, 1952, p.89).

With the passage of depressions winds commonly tend to veer (at present to west and NW) so that immediately after the cessation of precipitation drifting of snow into lee locations may take place in a slightly different direction from that at which it began. This secondary movement is only likely in eastern parts of the country where upland plateaux occur. In the West Highlands and the islands the opportunity does not arise, locations of rock walls there resulting from topographic alignment and the local wind direction during snowfall only (provided this factor is influential). Because local topography is so important to wind velocity it is unlikely that this basically statistical approach will yield much more in terms of defining the wind directions during glacial periods. A further step could be the application of models such as that proposed by Danard (1977) in which he derived an equation for the present mesoscale wind system that has terms to incorporate the topographical and basic meteorological data. The influence of snow blowing on altitude and azimuth of former glacier source walls has not been considered previously, however.

The size of plateaux upslope from rock walls varies systematically across the study area. The plateau area related to each rock wall was calculated as indicated in Chapter 2. Since, in terms of the process of snow blowing, upland plateaux have direction as well as size, the area related to each of the sectors (NE,SE,SW,NW) was obtained. A summary of the information is given in Table 8.3 and in complete form in Appendix 4. The table divides the data into regions and for each the number of former glacier source walls that are located next to a plateau for each direction is given, as well as the mean plateau area for those that are. Large differences in the opportunity for wind drifting of snow are revealed: the percentage that have plateaux in any direction increases eastwards. Only 3 from a total of 43 former glacier source walls on Skye are located beneath plateaux upslope and to the SW of them; in the Cairngorms 43 of 46 are located in this situation and the same trend is apparent in each of the other sectors. These values are not surprising: the variation in dissection of relief across Scotland has been widely discussed. However, the variation in plateau areas above rock walls has implications directly pertinent to this study.

Table 8.3 Plateau areas upslope from Rock Walls

	SE		SW		NW		NE		
	n	area(km^2)	n	area	n	area	n	area	%
Skye	2(5%)	0.05	3(7%)	0.07	0(0%)	0.00	0(0%)	0.0	30.0
W Highlands	49(30%)	0.07	68(42%)	0.06	8(5%)	0.05	3(2%)	0.12	19.8
SW Grampians	24(26%)	0.16	48(52%)	0.17	20(22%)	0.20	3(3%)	0.28	25.8
Monadhliath	12(33%)	0.26	31(77%)	0.21	16(41%)	0.22	5(13%)	0.07	37.2
SE Grampians	26(50%)	0.20	43(81%)	0.41	25(47%)	0.09	8(15%)	0.51	53.5
Cairngorms	22(50%)	0.39	43(93%)	0.27	22(49%)	0.35	8(17%)	0.10	52.2

Firstly, for any altitude, the area supplying snow to the glacier is the size of the surface area of the glacier itself in the western part of the field area, whereas farther east the accumulation area may in effect be increased by drifting from the plateau.

A quantitative example may be taken to illustrate the importance of this to the accumulation on an individual glacier if certain assumptions are made. Suppose that the glacier has an accumulation area of $0.25km^2$ with a plateau on its SW, the direction of the prevailing wind, of $0.3km^2$. Further, suppose that the annual precipitation total is 2000mm (water equivalent) and that 80% of this falls as snow (Manley, 1959). If 10% of the precipitation falling as snow on the plateau eventually comes to rest on the accumulation area of the glacier, an extra $48,000m^3$(w.e.) is received annually, which is equivalent to an extra 192mm of precipitation over the whole accumulation surface each year. Hence, even with a conservative estimate of the wind-drifted percentage reaching the glacier surface, the glacier receives as much as 12% more accumulation as the equivalent glacier with no plateau.

Secondly, the distribution of plateau areas and plateaux of different sizes in relation to rock walls supports the precipitation trend hypothesis of Chapter 6. The size of plateau related to a rock wall varies with time. When the rock wall is initiated two things occur: the area of plateau available to supply the rock wall increases as the crest length increases and simultaneously the glacier erodes back into the plateau thereby decreasing the plateau area. As erosion continues, however, the increase in the plateau area available to the rock wall ceases (for example when neighbouring rock walls expand to each other's borders). After this the area of plateau decreases as glacial erosion continues. The distribution of plateau areas across the study area suggests that the last stage has been reached in the West Highlands, and that erosion to, or past the preglacial topographic divides has occurred. In other places erosion to this stage has not taken place.

The configuration of plateaux also suggests that rock walls in the West Highlands have been etched so far into hillsides that there may be little enhancement of direct precipitation into lee positions by drifting snow. Despite this, the northern section of the West Highland Region and Skye contain many rock walls, and it has already been inferred that valley and ice cap ice was initiated in the southern West Highlands most frequently. Clearly, the lack of plateau areas did not inhibit the accumulation of snow. Since the rock walls also tend to occur at lower altitudes in these areas than farther east and north, it is suggested the precipitation gradient across the country was very steep and eastern and western parts of the study area had quite different precipitation regimes during periods of rock wall erosion.

The northwestward trend in rock wall altitudes superimposed on the main one in the SE Grampians indicates a precipitation gradient in this direction. However, since 85% of the rock walls in the area have large plateaux to the SW above their crests it may be argued that although precipitation was enhanced by orographic uplift at the Highland Boundary (the south-facing rock walls in Glen Clove are evidence of this) it fell off rapidly towards the highland interior, so that for example during the Loch Lomond Stadial a small ice cap could be sustained on the SE Grampian plateau (Sissons, 1972), but only a few small, high-level glaciers could be sustained in the northern Cairngorms (Sissons, 1979b).

In the preceding paragraphs it was suggested that rock walls are related systematically to plateau areas (or lack of them) according to the previously inferred precipitation gradient. It was inferred from the distribution of rock walls without plateaux that (i) the dissection of these uplands has occurred through glaciers eroding back to and across the preglacial divides and that (ii) in these locations direct accumulation of snow was sufficient to nourish glaciers without plateaux. However, particularly in the SE Grampians and the Cairngorms rock walls tend to be located beneath extensive plateaux. Plateau sizes in these regions vary greatly from 0-2km^2 and it is hypothesised that this should be reflected in rock wall morphometry. Two specific hypotheses were tested. Firstly, it is postulated that the larger the plateau area the lower will be the rock wall altitude, since the greater the accumulation of snow during the winter the lower the altitude at which a glacier may be sustained through the ablation season. Secondly, it is proposed that the greater the plateau area the greater the rock wall amplitude. This is suggested since previous studies have shown that the rate of glacial erosion is related to the total mass balance of a glacier, and erosion back into the hillside increases the rock wall amplitude until the topographic divide is reached. Although this hypothesis is more easily justified in a dynamic setting (i.e. where glacierization is occurring) it is proposed here on the assumption that backward erosion towards topographic divides would still occur in the SE Grampians and Cairngorms if glacial conditions were to be resumed.

These relationships are most likely to hold for plateau directions close to the wind direction during and immediately after the cessation of precipitation. The most significant correlation value ought to indicate the direct of the wind during and after snowfall.

The size of plateaux related to each rock wall is associated with the crest length of the wall; hence in order to analyse plateaux that are strictly comparable, plateau area was divided by the crest length. Further, the part of a plateau closest to the rock wall is likely to be most efficient in the transfer of snow and this was taken into account by using the natural logarithm of the plateau area/crest length ratio. Analysis has thus been carried out on a new variable:

$$P(dir) = \log_e(\text{plateau area/crest length}) \qquad (8.14)$$

where P(dir) is the direction in which the plateau extends behind the rock wall.

From Table 8.3 it is apparent that plateaux upslope and to the NE of rock walls are insignificant in both the SE Grampians and Cairngorms, as well as elsewhere. This is not surprising since many of the rock walls face this way under the combined influence of shading and leeward accumulation. If transfer of snow from the NE had been important a bi-modal distribution of rock wall aspects might be expected to have resulted in a northerly mode due to insolation effects and a southwesterly one due to drifting into lee locations. There is no indication of this from the data and hence NE plateaux are not considered further. To some extent NW is similar to NE; however, since one-half of all former glacier source areas do have plateaux to the NW this direction may not be so easily dismissed. Further data collection indicated that there is a much stronger locational relationship between plateaux to the west and rock wall position than between plateaux to NW and rock wall position. The trend analyses also showed a trend in rock wall altitude with a direction inclining toward NW indicating that this may have been close to the wind direction. These two considerations led to the calculation of plateau areas to the west for the SE Grampians and Cairngorms, and for completeness plateaux to the south were also calculated. Thence, plateaux from 4 sectors (that overlap to some extent) were analysed in the hope of distinguishing the dominant wind directions.

Table 8.4 indicates the results of correlation analysis in the Cairngorms (an area with no significant regional altitudinal trend). All the correlation coefficients are negative as

Table 8.4 Correlation between Rock Wall Base Altitude and Plateau in the Cairngorms (1)

P	n	r	p
SE	22	-0.4308	< 0.05
S	40	-0.1335	N.S
SW	43	-0.3509	< 0.03
W	37	-0.1015	N.S

(1) test: Spearman's correlation by ranks

Table 8.5 Correlation between Rock Wall Amplitude and Plateau in the Cairngorms (1)

P	n	r	p
SE	22	-0.4061	<0.06
S	40	-0.4159	<0.01
SW	43	-0.0770	N.S.
W	37	-0.4088	<0.01

(1) test: Spearman's correlation by ranks

as hypothesised. Highly significant results between rock wall altitude and plateau were found only for SW and SE plateaux although only half the rock walls have plateaux to the SE. Surprisingly, the results for south and west were not significant.

Table 8.5 shows the results of the correlation analysis between rock wall amplitude and plateau. The results were significant for three directions, but the correlation coefficients are all negative, which is the opposite of what was expected under the simple hypothesis proposed earlier.

The results suggest that the simple hypothesis is not sufficient to cover the dynamic nature of slope retreat through glacial erosion over time. Previously it was proposed that the lack of plateaux in the west of the study area is because here rock wall erosion has been most rapid. It is therefore suggested that, in an area much less suitable for rock wall erosion, retreat across the upland plateaux towards the topographic divide is still continuing. If rock wall erosion may continue until the divide is reached, as backward erosion occurs, so the amplitude of the rock wall is increased. The highly significant increase in amplitude with a decrease in plateau area in the Cairngorms for three separate directions may thus be explained in topographic terms rather than in terms of the size of the total glacier mass balance.

The inverse relationships between both rock wall altitude and amplitude and plateau area are thought to be responses to both slope retreat processes and variations in winter accumulation derived from snow drifting off plateaux. The larger the plateau the larger is the accumulation and hence the lower the altitude at which the glacier could be sustained through the ablation season. However, this explanation is only satisfactory in a comparative setting, but it has already been inferred from the distribution of plateau areas behind rock walls across the whole study area that the relationships should be considered dynamically. The simultaneous relationship between plateau area and amplitude may be viewed in terms of the retreat of the crest line break of slope towards the drainage divide through time. Under these conditions the increase in amplitude occurs while the plateau is itself being eroded. The increase in amplitude related to the decrease in plateau suggests that the erosion along and beneath the rock wall by the incipient glacier is more effective than the erosion of the plateau above through subaerial and periglacial processes. Hence as the glacier erodes backwards into the plateau the general altitude of the plateau is lowered more slowly and the amplitude of the rock wall increases. This would occur whether or not the rock wall base altitude is lowered greatly through time, the evidence of Chapter 4 being that altitude is not closely related to amplitude. By inference therefore the two negative correlations together indicate that rock wall (and cirque) erosion occurs backwards into the hill mass rather than downwards in altitude. If this were not so it might be expected that as the plateau area decreases, the altitude would decrease.

The above arguments in which the plateau area variable is understood to have a temporal and dynamic aspect must presuppose that in a small region such as the Cairngorms rock walls form in sites that optimise the use of plateaux for accumulation. Plateaux to the SW and SE are both highly correlated with rock wall altitude, but neither plateau to the south nor west is. The lack of significance with west suggests that winds from this direction were not important in transferring snow from exposed to lee locations. It is difficult to interpret the results from SW, south and SE together, save to postulate that winds from the SE could be the snow-bearing winds accompanying northeasterly to easterly moving depressions and that with the passage of each depression winds veered to a dominant southwesterly. Hence, snow would be accumulated in lee slope positions facing NW during snowfall and subsequently snow would be drifted from upland plateaux to NE-facing lee locations. This explanation requires that the veering of the wind through south was rapid, as it would be at the passage of the warm front itself. A second explanation lies in the mechanism by which snow is preferentially deposited during precipitation. All that is required for preferential accumulation on lee slopes while snow is falling is a sharp break of slope lying transverse to the wind direction; the size of the area upslope is not critical. This snow could fall during SE to southerly winds followed by a transference of fallen snow from exposed plateaux in the subsequent southwesterlies. Obviously in strong winds the plateau size plays a role because snow will not be deposited until it reaches the sheltered lee slope. This is probably why a correlation has been found between plateau to the SE and altitude rather than south, since, the winds preceding and at a warm front tend to weaken as well as subsequently veer following its passage.

The consideration that plateau size need not be important in assessing the wind direction during frontal snowfall may aid explanation of the regional distribution of azimuths shown in Fig. 7.3. In the West Highlands rock walls tend to face between north and NW whereas farther east the mode shifts to NE to east-facing. If plateau size is unimportant to accumulation during precipitation, in areas where there are no plateaux rock walls would tend to indicate the wind direction during snowfall only. In the eastern part of the field area this has been postulated to have a direction between SE and south, the SE component probably being due to the Highland Boundary location. In the west the alignment of east-west trending ridges has partially governed rock wall azimuth but southerly snow-bearing winds help to explain the lack of variability in azimuth. Farther east the greater easterly component in rock wall direction is partly caused by snow-drifting in southwesterly airstreams.

The Combined Effects of Insolation and Wind-drifting

Since (i) plateau area depends partly on aspect, (ii) insolation depends partly on aspect, and (iii) aspect depends to some degree on location (e.g. rock walls on the northern side of the Cairngorm plateau tend to face north), it is necessary to determine the relationship between these variables and rock wall altitude and amplitude more closely by removing the effects of location.

For 90 rock walls in the SE Grampians and Cairngorms multiple regression analysis was carried out with rock wall base altitude as the dependent variable. Independent variables entered in the equation were location in terms of easting and northing components, plateau areas and insolation factors. A regression design was used that entered the independent variables according to the significance of their partial correlation coefficients while controlling for variables already in the equation.

The location of the rock walls was entered first: on a linear surface location accounted for 48.0% of the variability in base altitude and is significant at the 0.001 level. P(SW) was entered next, raising the R value to 0.71. The inclusion of the insolation value increased this to 0.73 and P(SE) to 0.74, thereby explaining 54.9% of the total variation in rock wall altitude, the final result being significant at the 0.001 level.

A similar regression design was used to establish any relationships between rock wall amplitude and azimuthal variations. Since location is a less crucial factor to rock wall vertical development than altitude, locational coordinates were not forced into the equation initially, and the design indicated above was applied to all the independent variables. Northing was the first variable to be entered with an r value of 0.23. P(SW) was entered next, the partial correlation coefficient of -0.20 being significant at the 0.1 level but not at 0.05, and R was increased to 0.30. The total explanation of 9.1% is significant at the 0.05 level. The addition of P(S), P(SE), P(W) and the insolation coefficient did not increase the explanation sufficiently to warrant their inclusion. The low multiple correlation coefficient and barely significant result indicates, as suggested in earlier chapters, that amplitude is not greatly affected by regional climatic controls and also shows that local site variations which effect the climate within the rock wall areas are insignificant.

The multiple regression analysis of rock wall altitude included both regional and local scale independent variables. The analysis indicates the importance of both site and aspect in the location of glaciers that erode rock walls since these variables explain almost 55% of the total variation in the altitude of rock wall bases. Of the local climatic variables that combine to determine the aspect of rock walls plateaux to the SW are most important as this variable was included earliest in the equation. It was followed by the insolation coefficient and plateaux to the SE. These results suggest that variation in rock wall base altitude over short distances in the Cairngorms and SE Grampians is governed by the initial topography: rock walls are most likely to have been eroded by glaciers formed on the northeastern sides of upland plateaux. It is inferred from the order in which the independent variables were entered in the equation that this is primarily because of the advantages in terms of accumulation through windblown snow rather than to protect the glacier from loss by melting due to insolation during the ablation season.

The relative lack of importance of SE substantiates the earlier suggestion that during frontal snowfall winds veer rapidly from south-SE at the warm front where most of the snow falls, to SW following the passage of the depression system. The south- to SE-facing rock walls near the Highland Boundary also indicate a southeasterly wind direction with increased falls of snow in the updraught of air at the Highland Boundary. When snowfall has ceased it is only the snow that rests upslope of the rock wall that can increase accumulation on the glacier; the extra accumulation is proportional to the area of the plateau on which is was initially deposited.

The importance of P(SW) over the protection from insolation indicates that the critical factor in the location of glaciers, during each glacial period, was whether or not accumulation was sufficient and that in most cases this was only so if snowfall was aided significantly by windblown snow. This substantiates the proposal that much of the north and east of the country had relatively low precipitation rates during many periods of partial glaciation.

Summary and Conclusions

1. The rock wall insolation model has been used to study that part of global radiation that varies with aspect. The model has been used in two ways: firstly, to study how the wall itself modifies the mesoscale climate by curtailing the receipt of insolation on slopes facing north, and, secondly, by analysing statistically the relationship between altitude and aspect through the influence of insolation.

2. The model shows that at the base of the rock wall there is a significant decrease in the potential direct insolation available to north-facing rock walls. Slope and direction together mean that rock walls facing north receive as much as 70% less than the insolation available to a flat surface whereas south-facing ones receive up to 15% more.

3. The insolation model was used to obtain a correlation coefficient between irradiation and rock wall altitude over part of the field area. The correlation coefficient was positive and significant at the 0.1 level. Its positive nature concurred with the postulate that an increase in insolation must be accompanied by a compensating decrease in temperature through a rise in altitude. If compensation is made for the time lag between radiation receipt and temperature change the correlation coefficient is increased.

4. The partial correlation analyses that considered the relationship between rock wall altitude and insolation, after abstracting the variation in altitude due to location, showed that insolation, with allowance made for air temperature lag, varies significantly.

5. The relationship between rock wall locations and upland plateaux varies over time and with the severity of glacial

erosion. In much of the west of the field area plateaux are small or are absent, whereas in the east rock wall crests are commonly backed by rolling uplands. This distribution of plateau areas concurs with the inferred precipitation trend. Rock wall glaciers in the west have had the highest net and total mass balances allowing them to erode into the hill mass to or beyond the preglacial watersheds. In the east of the study area rock wall sites are a function of the upland topography, tending to occur along the northern and eastern edges of the upland plateaux.

6. A negative correlation coefficient was found between rock wall amplitude and plateau size in the Cairngorms. This emphasises the importance of erosion back towards the pre-glacial watershed. The smallness of the contribution that wind-drifting and insolation make to the overall variability in amplitude suggests that local climatic factors are not the most important variables controlling rock wall amplitude.

7. Local climatic variables are important in explaining the local variation in rock wall basal altitude. P(SW) and P(SE) are both significantly correlated with rock wall altitude. The multiple correlation analysis in which P(SW), P(SE) and the insolation coefficient, as well as location, were entered explained 55% of the variation in rock wall altitude. The larger partial correlation coefficient between P(SW) and altitude than between insolation and altitude suggests that drifting into lee locations under the influence of southwesterly winds is the most significant feature of rock wall azimuthal distribution in the east of the study area.

CHAPTER 9

FORMER GLACIER SOURCE WALLS, CIRQUES AND LOCH LOMOND ADVANCE GLACIERS

Introduction

Most glacier source walls in the study area form parts of cirques. In the first section of this chapter the relationship between rock walls and their cirques, or whole source areas, is discussed with two aims. Particular attention is paid, first, to the usefulness of morphometric parameters of whole cirques compared with rock walls in considering the relationship between source locations and their environment and, secondly, to the relationship between cirque shape and environment during glacierization.

Later in the chapter the role of source areas during the Loch Lomond Advance is considered by treating the whole population of source areas as the maximum potential number of source sites available for glacierization. In this way the Loch Lomond Stadial environment may be analysed as a unique partial glaciation.

Much of this chapter is written with particular reference to source areas in the Cairngorm Region since the source areas here are well-formed and clearly defined. Most of these source areas were also formed independently of each other so that cirque shape is not affected by this source of variation. Of all the regions of the study area this is the one in which ice external to the source areas appears to have had least effect.

Defining the Cirque

The broad definition of a cirque given by Evans and Cox (1974) was quoted in Chapter 2 and was the starting point for identifying and delimiting the features in this study. To allow for cases in which there is no increase in gradient in front of the cirque floor that particular definition of a cirque did not include a downstream boundary. In practice, it is necessary to delimit objectively the 'zone of influence' of the cirque source area and several authors, including Evans (1974) asserted that a lip is almost always present, although it need not have been formed by the processes of cirque formation, but may relate to the underlying rock structure (e.g. Evans, 1974, p.118).

In this study any downstream increase in gradient below the cirque floor was used to determine the boundary, as in Coire an 't-Sneachda (Fig. 9.1). Where the cirque lies on the side of a trough (e.g. the east-facing cirques near Loch Einich) the trough side wall was used to delimit the cirque. Major problems occur at valley heads where rock head walls merge into valley sides and there is no appreciable steepening of the valley beyond the cirque floor. This problem arose in Coire an Lochain in which the cirque lower boundary was drawn where the valley side changed appearance from its characteristic side wall to the unaffected valley side wall.

Cirques in the Cairngorms

All but four of the former glacier source walls in the Cairngorms occur in association with cirques and are shown in Fig. 9.1. Some of these cirques have much longer crest lengths than have their related rock walls. For example, Coire an Lochain and Coire an 't-Sneachda are much larger than their rock walls, the floor area of each of these cirques extending a long

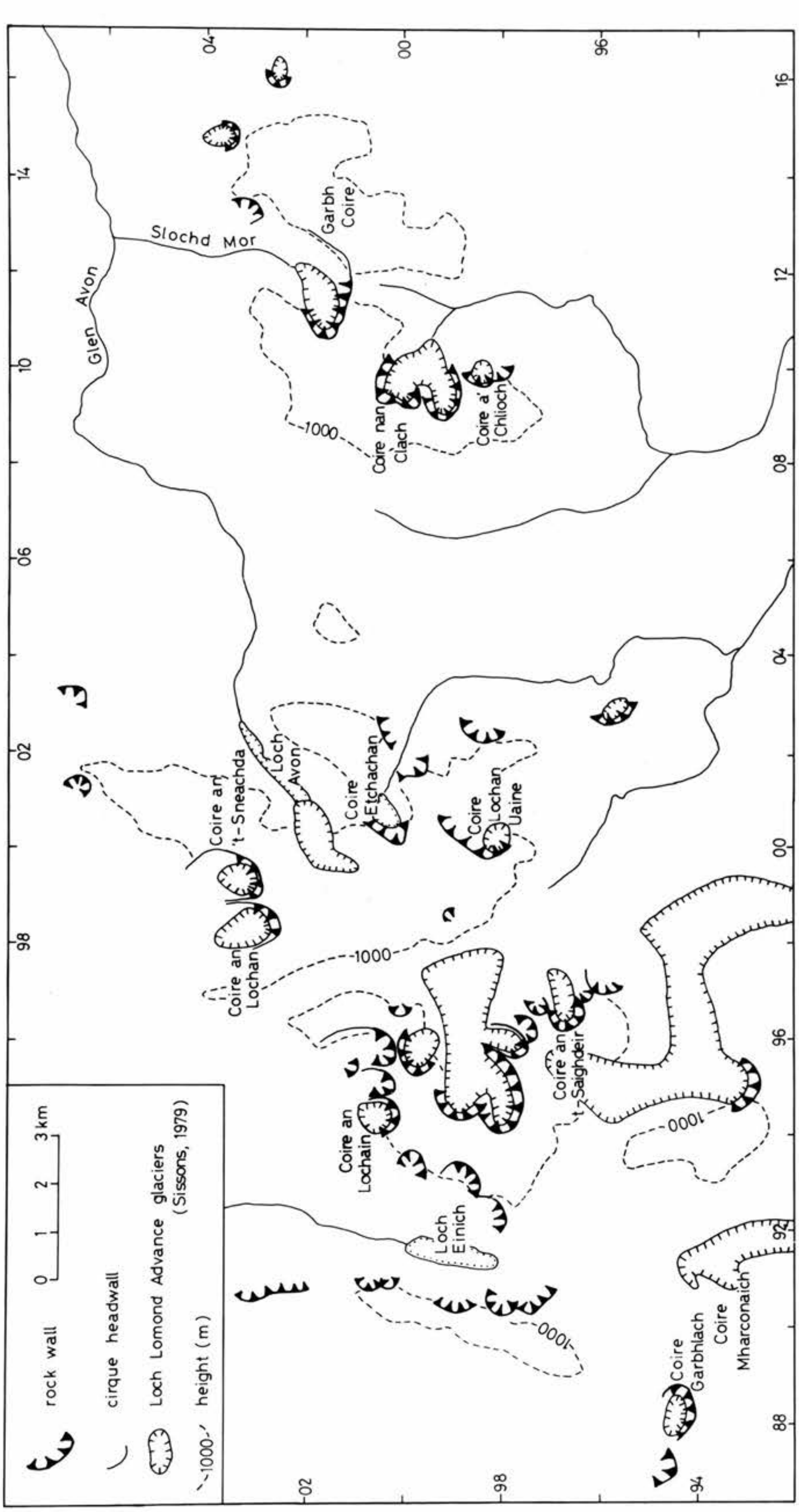


Fig. 9.1 Rock Walls, Cirques and Loch Lomond Advance Glaciers in the Cairngorms

way from the rock wall. In Garbh Coire one side wall extends far down the NW-facing side of the valley. The cirques bordering the west side of Gleann Einich have especially poorly developed floor areas.

The cirques in the Cairngorms have been studied by Sugden (1969) and their part in the Loch Lomond Advance by Sissons (1979b). Sugden was so impressed by the regularity of outline that he fitted semi-circles to cirque crests, ignoring variations in side wall length. He found cirques have a strong overall tendency to face eastwards but that they may face NW, and attributed this to opportunities arising from the way the mountains face.

Cirque Morphometry

Morphometric analysis was carried out following data collection from 1:25,000 maps this being aided by reference to aerial photographs. Values were obtained in a similar manner to those for rock walls (Chapter 2). Wall crest and base altitudes were found at 100m intervals along the cirque head and side walls; wall gradient and azimuth were also obtained, the latter to the nearest 22.5^{o}. In addition the total depth of the cirque, its longitudinal axis length and azimuth were measured. Following Evans (1974, p.118) the longitudinal axis was defined starting from the lowest point on the cirque floor (excluding fluvial notches) and extended towards the backwall at right angles to the floor contours. In contrast to the method used by Sugden (1969) and Unwin (1973) this need not bisect the cirque since the proportion of cirque area on either side of the axis may vary. Using this definition of the longitudinal axis, the cross-sectional asymmetry of the cirque may be examined. Cirque asymmetry about the axis was quantified as the ratio of cirque width on either side of the axis to the total width at the widest part of the cirque.

Variation in Morphometry between Cirques and Rock Walls

Following data collection, the morphometric variation between the cirque and rock wall portions of former glacier source areas in the Cairngorms was examined.

(1) Gradient. The mean slope angle of the 17 cirques that have both rock wall and non-rock wall portions is 35.2^{o}. The mean angle of the rock wall slopes is 37.4^{o} while that for the rest is 32.9^{o}. A one-tailed Student's t test showed that the difference is significant at the 0.005 level.

(2) Amplitude. A Student's t test was also employed to test if rock wall amplitudes are greater than the amplitudes of the rest of the cirque walls. The non-rock wall portions of cirques have a mean amplitude of 143.4 ± 55.6m while that of rock walls is 156.6 ± 45.9m. The t test value of 0.526 indicated no significant difference between the samples.

(3) Altitude. No statistical variation in the altitude of rock walls and non-rock wall portions within cirques was found. The base altitude of the former has a mean of 919 ± 116m while that of the latter if 888 ± 117m. A Student's t test value of 0.75 was not significant at the 0.1 level.

The initial premise in carrying out this study was that, since rock walls are believed to be the parts of cirques that are the initial sources for glacier accumulation, they are the parts of source areas that would be most affected by erosion. Therefore rock wall slopes and amplitudes should be larger, and altitudes lower than in corresponding non-rock parts of cirques. In fact, the only tendency displayed is for gradients of rock walls to be steeper. In some cirques the rock wall amplitude is greater than the rest, the overall tendency being for amplitude to decrease at either end of an isolated cirque. Elsewhere the head wall slope continues into an elongated side wall such as in Garbh Coire and the amplitude increases down valley. Similarly, the altitude within a cirque may vary with position within the mountain mass, the mean rock wall altitude generally being below that of the rest of the cirque, but occasionally being above, examples of the latter being Coire Garbhlach and Coire and Lochain.

Cirque and Rock Wall Aspect

Fig. 9.1 shows that the extension of cirque headwalls beyond their rock wall crests is not symmetric about the rock wall median axis, rock walls frequently being extended on NW- and west-facing sides of cirques. This suggests that there may be a difference in axis aspect between cirques and rock walls. Evans (1974) considered that the aspect of rock walls within cirques would be less likely to deviate around an average than cirque axis since the source wall is more closely related to cirque erosion. It is hypothesised that in the Cairngorms rock wall axes vary less than cirque axes.

Cirque longitudinal axis was compared directly with rock wall median axis using vector analysis. The resultant mean vector direction for rock wall median aspect and cirque longitudinal axes respectively were N52^{O}E and N55^{O}E. Vector strengths were 42.6% and 44.8%. The variations were found to be statistically insignificant at the 0.05 level, which is not surprising because of the crudeness of the initial azimuthal measurements.

The variation in azimuth between cirques and rock walls was subsequently analysed using individual headwall segment values. Rose diagrams (Fig. 9.2) were drawn for each. The rock wall resultant vector is N60^{O}E, while that for cirques is N56^{O}E with vector strengths of 41.5% and 33.8% respectively (Table 9.1). A Chi-square test yielded a value of 21.62 which, with seven degrees of freedom and sample sizes of 530 and 603, was

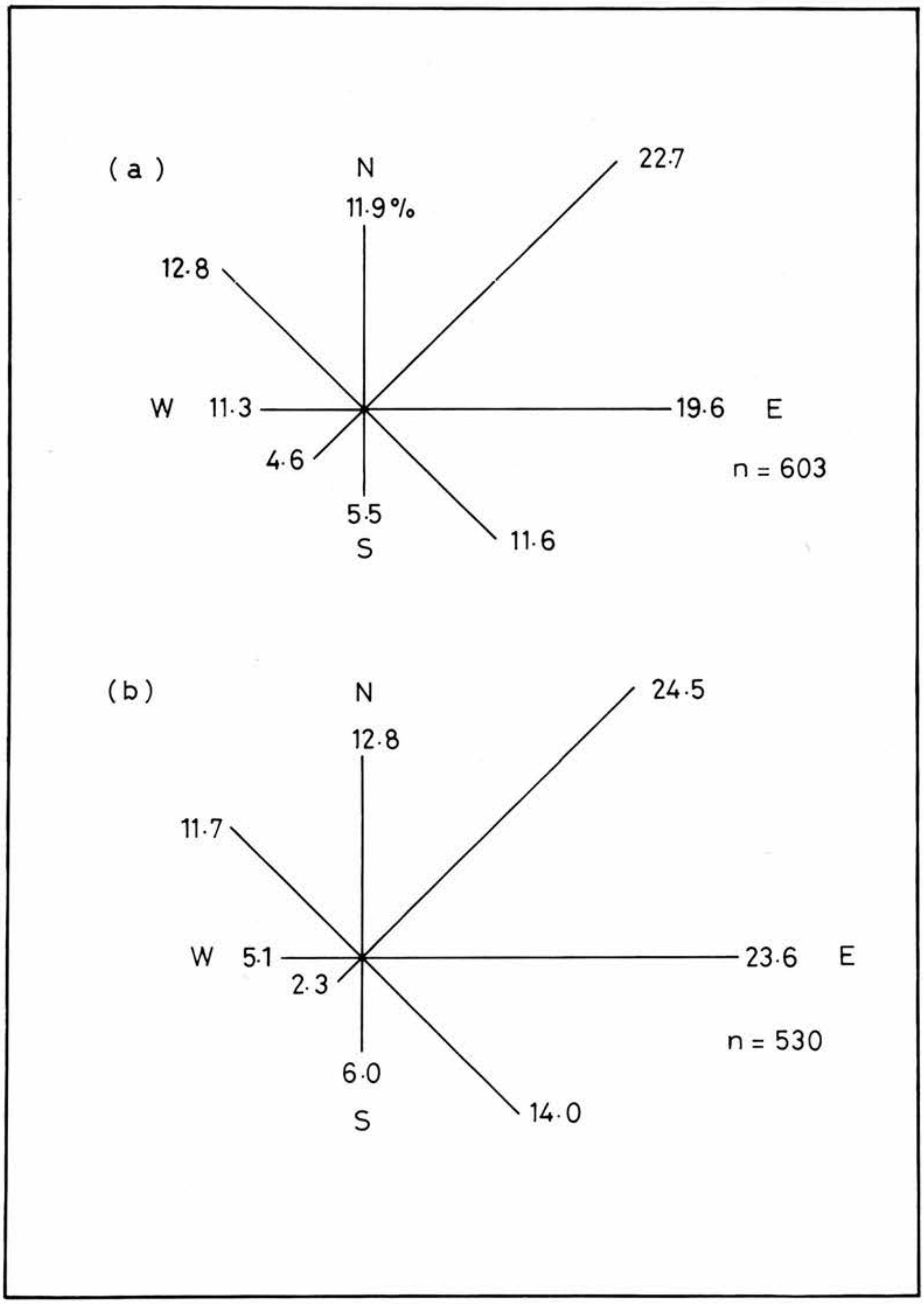


Fig. 9.2 Aspect of Individual Portions of (a) Cirques and (b) Rock Walls in the Cairngorms

Table 9.1 Rock Wall and Cirque Aspect in the Cairngorms

		resultant vector $E^{o}N$	magnitude	strength(%)
Cirque	Individual points	56	203.8	33.8
	Long axis	55	17.0	44.8
Rock Wall	Individual points	60	220.0	41.5
	Long axis	52	21.3	42.6

significant at the 0.01 level. Three points arising from this are that (i) there is little variation between cirque individual and axis resultant vectors while the same parameters vary quite widely for rock walls; (ii) the cirque axis lies slightly east of that for rock walls the opposite being true of individual measurements; and (iii) the strengths of these vectors vary for cirque measurements but not for rock walls.

The first of these points concerns the variation in orientation and elongation between cirques and rock walls. Cirques are almost symmetrical in aspect distribution about their longitudinal axes, the sum of the individual point vectors being almost the same as that for long axes. The mid-point rock wall resultant vector direction has a greater northward component than the individual point vector counterpart. Rock walls do not display the symmetry associated with cirques. The preponderance of east-facing rock wall segments accounts for the difference between mid-point and individual resultant vectors. That cirques are symmetrical while rock walls do not tend to be, supports the argument that cirque shape is not entirely due to erosion by ice accumulated below steep slopes since different parts of the same cirque can face in diametrically opposed directions, one of which may be detrimental to the accumulation of glacier ice.

The second point concerns the actual resultant vector directions. Elsewhere (e.g. Lewis, 1970) it has been shown that glaciers may originate on south and west side walls of cirques and not necessarily along all walls. The variation in resultant vector direction between individual point vectors and rock walls in the Cairngorms (Table 9.1) is significant. The cirque resultant has a greater northward component than rock walls, the distributions being drawn in Fig. 9.1. Portions of cirque headwalls are twice as likely to face west or SW as rock walls, although the actual probabilities remain small.

Thirdly, the degree of clustering of individual vectors about the resultant vector varies between rock walls and cirques. There is little difference in vector strength between cirque long axis and rock wall long axis (Table 9.1). This is not surprising since the measurement divisions are crude. However, there is greater variety in the measurement of individual segments, rock wall vector strength being higher than cirque vector strength, the difference being due to much lower strength for cirque segments than long axes. The degree of clustering is a useful qualitative measure of variation between distributions where the resultant vector directions are not greatly different. The difference between cirque long axes and individual point vector strengths is due to the consistency in long axis direction while individual portions of each headwall vary. That the same sort of variation is not indicated in rock wall aspect clustering shows that rock wall aspect is much less variable than cirque aspect.

All the points made above indicate that the rock wall segments of cirques show much less variation in aspect than the remainder. Since the rock walls in almost all cases form part of cirques it appears that they consistently form the east-to-northeastward facing segments of whole cirque headwalls. Where the rock wall part itself is not symmetrical about its axis the headwall frequently includes a non-rock wall portion that is not dependent on conditions at the onset of glacierization.

Cirque Shape

Much emphasis has been placed on the study of cirque shape through two-dimensional curve drawing and various morphometric shape ratios, in attempts to explain cirque erosion and the relationship between cirques and their environment (e.g. Haynes, 1968; McLaren and Hills, 1973; Embleton and King, 1975). The usefulness of either type of shape analysis in defining cirque erosion mechanisms or the severity and length of cirque occupation has yet to be demonstrated. In this chapter the asymmetry of cirque profile and two morphometric ratios are discussed. In each case the aim of the study is twofold: (i) to assess the usefulness of the indicators and (ii) if useful, to consider what they indicate.

Cirque Asymmetry

Earlier in this chapter it was shown that cirques are generally symmetrical about their longitudinal axis although rock walls are not necessarily so. While studying cirques a general impression was gained of internal asymmetry about the longitudinal axis. No references have been found to this cross-profile asymmetry in the field literature, although in a diagramatic representation of a cirque Andrews and Dugdale (1971) indicated strong asymmetry. In a theoretical study that involved fitting elliptic curves to cirque cross-profiles Aniya (1974) found that in each case, while one side of the cirque closely fitted the expected curve the other did not.

Since cirques in the Cairngorms are symmetrical about their longitudinal axis and the gradient of rock wall portions of cirques is steeper than the remainder, an asymmetrical cross-profile is likely to result. The parts of cirques facing east or NW should have steeper walls and narrower floors than the glacially less favoured aspects.

The asymmetry of each cirque was measured by comparing the maximum width (in plan view) on either side of the longitudinal axis, each measurement being expressed as a proportion of the total width. The values are given in Table 9.2 for each long axis direction. There is a tendency for the northern sides of eastward facing cirques to be wider than the southern, although the difference using a Mann-Whitney U test is not significant at the 0.05 level. The other azimuthal opposites show no varying tendencies whatsoever.

Table 9.2 Cirque Cross-Profile Asymmetry

(a) Maximum floor width (mean) as proportion of total width
(b) Maximum total width (mean) as proportion of total width

	N	NE	E	SE	S	SW	W	NW
(a)	0.535	0.523	0.458	0.525	0.465	0.476	0.542	0.475
(b)	0.565	0.506	0.550	0.520	0.435	0.494	0.450	0.480

This method of assessing asymmetry of cirque cross-profile is crude since in most cases both sides of the longitudinal axis contain rock source wall and non-rock cirque wall parts. The size of the variation between northern and southern sides of east-facing cirques suggests that asymmetry does occur with the long axis lying closer to the source wall section of the cirque. Further study of asymmetry would be profitable if carried out through profile curve fitting such as that done by Haynes (1969) for longitudinal profiles in conjunction with detailed mapped evidence of glacial source areas.

Morphometric Ratios

Many authors have used elements of cirque shape to indicate the depth of erosion that has taken place through incision of the cirque in the mountainside. Manley (1959) was first to relate cirque length to depth. He found that this ratio is commonly between 2.8:1 and 3.2:1 in the English Lake District. On Baffin Island Andrews and Dugdale (1971) found a median ratio of 4.3:1 and Gordon (1977) found a median of 2.1:1 in part of northwestern Scotland. The present writer's measurements show that cirques in the Cairngorms have a length to depth ratio of 2.6:1, ranging from 1.2:1 to 5.3:1.

The variation in this ratio between the Lake District and Baffin Island led Embleton and King (1975, p.210) to suggest that cirques in the latter area are significantly more deeply cut into the mountain range than those of the former area despite the large operator differences. Andrews and Dugdale (1971) suggested that differences in the length to depth ratio are due to differences in basal ice temperatures. The much lower median in the NW Highlands may stem from the inclusion of many short secondary cirques in Gordon's study. The topographic differences between that area and the Lake District are a further contributing factor. The Lake District, like the Cairngorms, contains many cirques lying at the heads of radiating valleys, while the cirques in Gordon's area occur along the sides of deep glacial valleys and breaches where longitudinal development is less likely.

In the Cairngorm cirques long axis length tends to vary largely with topographic situation. Cirques at valley and trough heads, and those where glacier ice could move directly out from the source, tend to have longer axes than those in trough and valley sides, and cirques in the former situation also tend to be larger. The length/depth ratio shows a strong positive correlation with cirque area ($r = +0.57$, $n=40$, $p < 0.01$). Thus the larger the cirque, the greater the backward development in relation to the area. From this however, it is not necessarily correct to infer that differences in length/depth ratios are necessarily related to in situ glacierization factors. Rather, there are two, not mutually exclusive, possibilities. Firstly, the differences are indeed due to longer or more severe glacierization and secondly, that cirque site relative to external ice masses eroding the cirque is significant.

To investigate the importance of cirque site in relation to ice masses from outside the cirque, the Cairngorm cirques were classified according to site into two groups: (i) at valley or trough heads and sites leading directly away from the mountains (least likely to be eroded by external ice masses), and (ii) those on valley sides and facing into the mountains (most rapidly affected by ice accumulated up valley). A Mann-Whitney U test was used to test the hypothesis that cirques in the former class have higher length/depth ratios than those in the latter class becauses of their sites. The test ($N_1 = 18$, $N_2 = 23$, $R_1 = 461.5$, $R_2 = 399.5$, $U = 290.5$) indicated the two classes were different at the 0.05 significance level. The median of the group of least affected cirque sites is 2.87 whereas that for the other sites is 2.31.

This result supports the findings of Chapter 4 concerning rock walls themselves. There it was found that rock walls in those regions that display the severest signs of glaciation tend to be among the smallest in amplitude and area. It was proposed that this is because cirques in the areas most frequently and earliest to be glacierized in any climatic deterioration were also those most rapidly over-run by external valley or piedmont ice. Similarly the cirques in sites most often exposed to valley ice moving normal to their longitudinal axes, such as those situated on trough sides (e.g. in much of the NW Highlands or the west side of Gleann Einich in the Cairngorms), would have relatively shorter longitudinal axes.

The use of the length/depth ratio as a measure of depth of incision and hence severity of erosion is not always valid when the ratio is also related to different periods of subjection to erosion by external ice. This discussion is based on results within a small area and in no way excludes possible differences in cirque shape due to variations in basal ice characteristics in different environments.

A second shape ratio that may relate to cirque erosion is the plan curvature of the headwall. Evans (1974) measured this as the number of degrees the longest headwall contour travels through from one end of the cirque to the other. The method has since been used by others, including Gordon (1977). A simpler technique was used here, the profile curvature being measured as the ratio of the crest length to the maximum cirque width. As the cirque becomes more incised into the mountainside the crest length increases more rapidly than the width. The crest length itself is normally the longest profile delimitor in the cirque provided the headwall is not a vertical cliff, and its length is easily measured. This measure of profile curvature would be particularly suitable in areas where large scale photogrammetrically contoured maps are not available.

The median crest length/width ratio for Cairngorm cirques is 1.6:1, values ranging from 0.65:1 to 4.5:1. The ratio is very consistent, with 25 of the values lying between 1.2:1 and 1.9:1, six lying below and nine above. Those cirques that have high plan closure values are not necessarily the largest cirques. (The correlation coefficient between plan closure and cirque area is 0.28, which is only significant at the 0.1 level.) Unlike the longitudinal profile descriptor a Mann-Whitney U test revealed no significant difference in the crest length/width ratio between isolated cirques and those on valley sides.

The Usefulness of Cirques in a Study of Sites of Local Erosion

The shape parameters studied here have helped little in explaining the growth of the cirques as sites of local glacial erosion or in explaining why they have certain azimuths and magnitudes. However, as was hypothesised, cirque aspects are more widely distributed azimuthally while non-rock wall segments or cirque headwalls are less steep than their rock wall counterparts. Amplitude and altitude vary insignificantly between rock wall and non-rock wall parts of cirques, variations depending on external topographic factors rather than the altitude of accumulation of snow and ice. These variable features of cirques are in accord with the view expressed in Chapter 2, where it was considered impossible to demarcate cirques consistently and accurately except in their rock wall zones. That the latter vary less in azimuth and are steeper, while amplitude and altitude depend on topography is evidence of the closer relationship between rock wall and glacier source than whole cirque and glacier source. In a thesis concerned with erosion by highland ice sources, the collection of data concerning whole cirques yields little new information.

The morphometric ratios show, despite problems of cirque lip location, just how little cirque shape varies, but the importance of site to the length/depth ratio within the Cairngorms is indicated. This is reinforced by the location of the rock walls that are not parts of cirques. Of the four former source walls that were not considered to form parts of cirques three were excluded because of their poor floor development. These rock walls, particularly Coire Lochan t-Seilich and the northern cliffs of Coire Etchachan (Fig. 9.1), are located where ice external to the features would have built up rapidly and encroached upon their frontal aprons in any period of glacierization.

The crest length/width ratio is of little use in this form of local study because it varies little. It may be more useful when comparing cirques formed in greatly differing environments. However, differences are as likely to be due to rock type as to the glacial environment. The study of morphometric ratios does not appear to aid the study of source area erosion. However, it is the floors of source areas as well as the rock wall zones that were occupied by glacier ice during partial glaciation and it is the latter that are now considered.

Glacier Source Areas during the Loch Lomond Stadial

In this thesis the Loch Lomond Advance has frequently been used as an example of partial glaciation. Here the approach is different. The population of former glacier source areas is assumed to represent closely the total population of all possible highland ice source locations, thereby presenting an opportunity to study the Loch Lomond partial glaciation as a separate event in the erosion of source walls. The variance between the total population and those occupied during the Loch Lomond Stadial is related to the singularity of that event.

Many studies of formerly glaciated areas laid emphasis on equilibrium firn line altitude. The relationship between this and source wall base altitude across the field area is also considered.

Source Area Occupation by Loch Lomond Advance Glaciers

The Loch Lomond Stadial has been widely studied and inferences made concerning the climatic environment from geomorphological and palynological evidence. This evidence was reviewed in Chapter 1. In much of the present field area glaciers extended beyond the stage of discrete bodies of ice. In the western Highlands, although ice did not cover the summits, accumulations were large with ice from highland source areas converging to form valley ice streams. In the Ben Nevis area and Mamore Forest ranges, Thorp (1979) found evidence for large coalescent valley glaciers emanating from cirques, but towards the eastern end of the ranges he noted a source area that had not been occupied since the Late Devensian ice-sheet. Farther east detailed studies of the geomorphological evidence (Sissons, 1972; Sissons and Grant, 1972; Sissons, 1979b) have shown not only that during the Loch Lomond Stadial many glacier source areas contained independent ice masses but also that many source areas were not occupied. In particular, in the Cairngorms there is evidence of glacierization in less than half of the source areas. The object here is to discover why some source areas in the Cairngorms were occupied by glaciers at this time and some were free, in order to assess the individual nature of the Loch Lomond Advance as a partial glaciation.

The most recent and comprehensive study of the Loch Lomond Advance glaciers in the Cairngorms is by Sissons (1979b). The limits of the ice at its maximum extent published in that study are indicated in Fig. 9.1. Only two Loch Lomond glaciers did not form beneath source walls as defined in the present study. The glacier at Coire Mharconaich, SW of the main Cairngorm massif, lies below a rock wall of low amplitude and gradient that was excluded during the initial data analysis. The Glen Avon trough head contained a glacier but the trough head was not considered to be a true rock wall since it is breached by several streams.

The match between source walls and glacier sites varies across the map. In the eastern Cairngorms the correspondence is highest; six of the seven rock wall source areas contain evidence of occupation during the Loch Lomond Stadial. Farther west in the central Cairngorms not all rock walls were occupied, while in the extreme NW along either side of Gleann Einich no rock walls were source sites for Loch Lomond Advance glaciers. However, the largest volumes of ice occurred on the south-western side of the mountains.

In order to identify the factors primarily responsible for the location of glaciers a correlation matrix (Table 9.3) and rose diagrams (Fig. 9.3) were drawn. The table shows that the shape, size and altitude of rock walls occupied and free vary significantly. Those occupied by glacier ice occur at significantly higher altitudes, are of significantly greater amplitude and area, and occur closer to the mountain summits, but have slopes not significantly steeper than the free rock walls. This is in accord with Graf (1976) who found the amplitude of cirques in the Rocky Mountains to be a good indicator of whether or not cirques are presently occupied. That the glacierized source areas were larger might suggest that these source areas have been advantageously located during many similar partial or mountain glaciations. During any glacierization the same sites tend to be glacierized first and hence eroded longest. A positive feedback effect could be expected in that those sites that are most frequently eroded

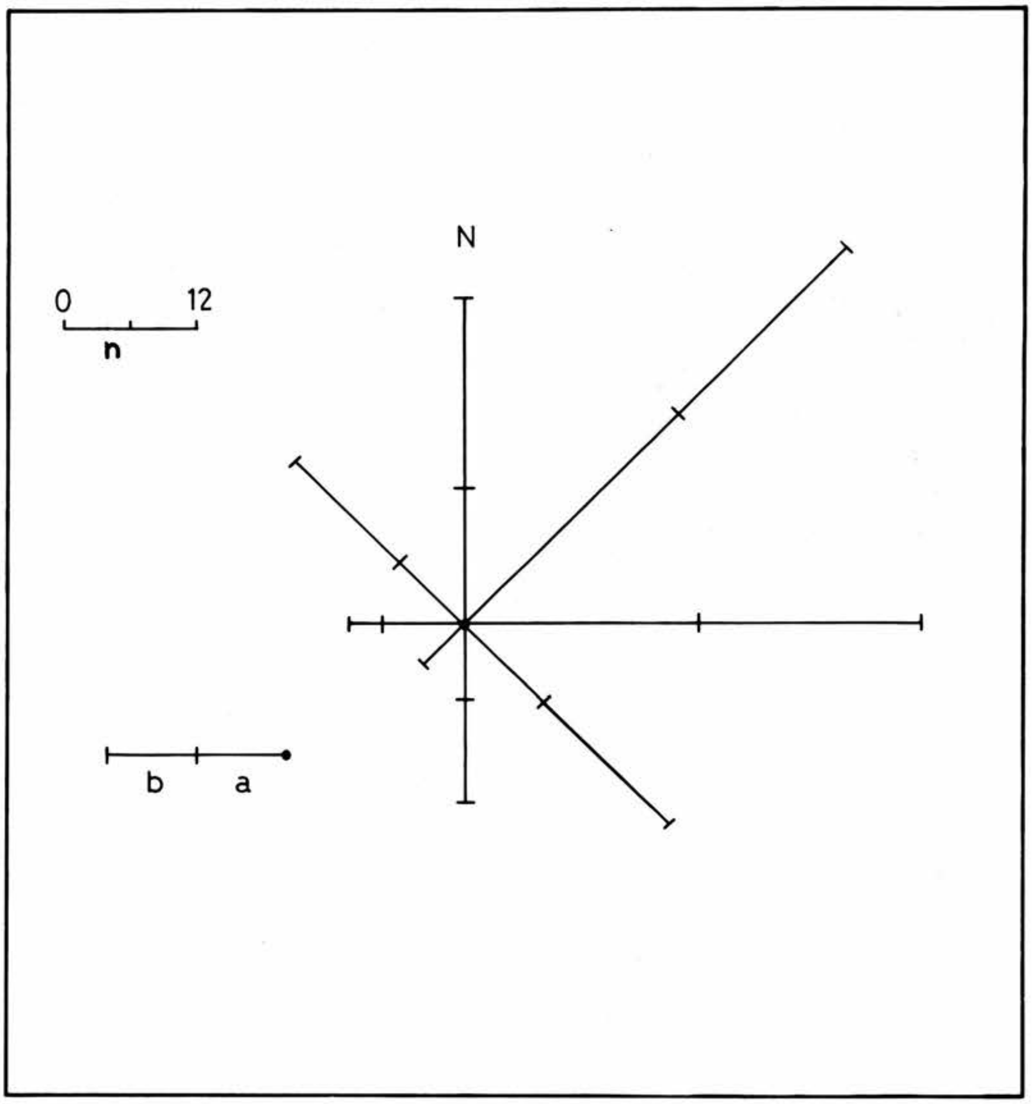


Fig. 9.3 Aspect of Glacierized and Unoccupied Source Areas during the Loch Lomond Advance

Table 9.3: Morphometric Variations between Empty and Occupied Source Areas in the Loch Lomond Stadial

	Measure of Central Tendency (1)	Occupied	Empty	Significance of Difference
Amplitude	a	172.1	140.1	0.01
Area (km^2)	b	0.610	0.232	0.001
Base Altitude (m)	a	927.4	863.0	0.05
Crest Altitude (m)	a	1099.5	1003.1	0.01
Summit-crest Alt. (m)	a	76.1	110.7	0.005
Gradient (degrees)	a	38.2	36.9	N.S.
Plateau to SW (km^2)	b	0.317	0.198	0.001
Plateau to S (km^2)	b	0.387	0.226	0.001
Plateau to SE (km^2)	b	0.186	0.190	N.S.

Notes (1) a represents the mean used with parametric test
b represents the median used with non-parametric test

should be deeper, more incised and steeper, thus allowing greater shade during subsequent glacierizations. This does not seem to be so, however, since the glacierized and non-glacierized rock walls lack significant differences in back wall slope or incision (as measured using cirque morphometric ratios). The lack of variance in rock wall slope suggests that the most important factors determining the slope angle are periglacial activities, such as freeze-thaw action on the free face above the glacier. This is compatible with the idea that a cirque glacier obtains most of its debris supraglacially from the exposed rock walls at its head, rather than from below the scarcely moving ice (Boulton, 1974).

Occupied glacier source walls tend to occur at higher altitudes than others. Fig. 9.4 is a dispersion diagram of the altitudinal variables. The basal altitudes of glacierized rock walls cluster around 960-1010m while those that were not occupied are more widely dispersed, with many around 800m.

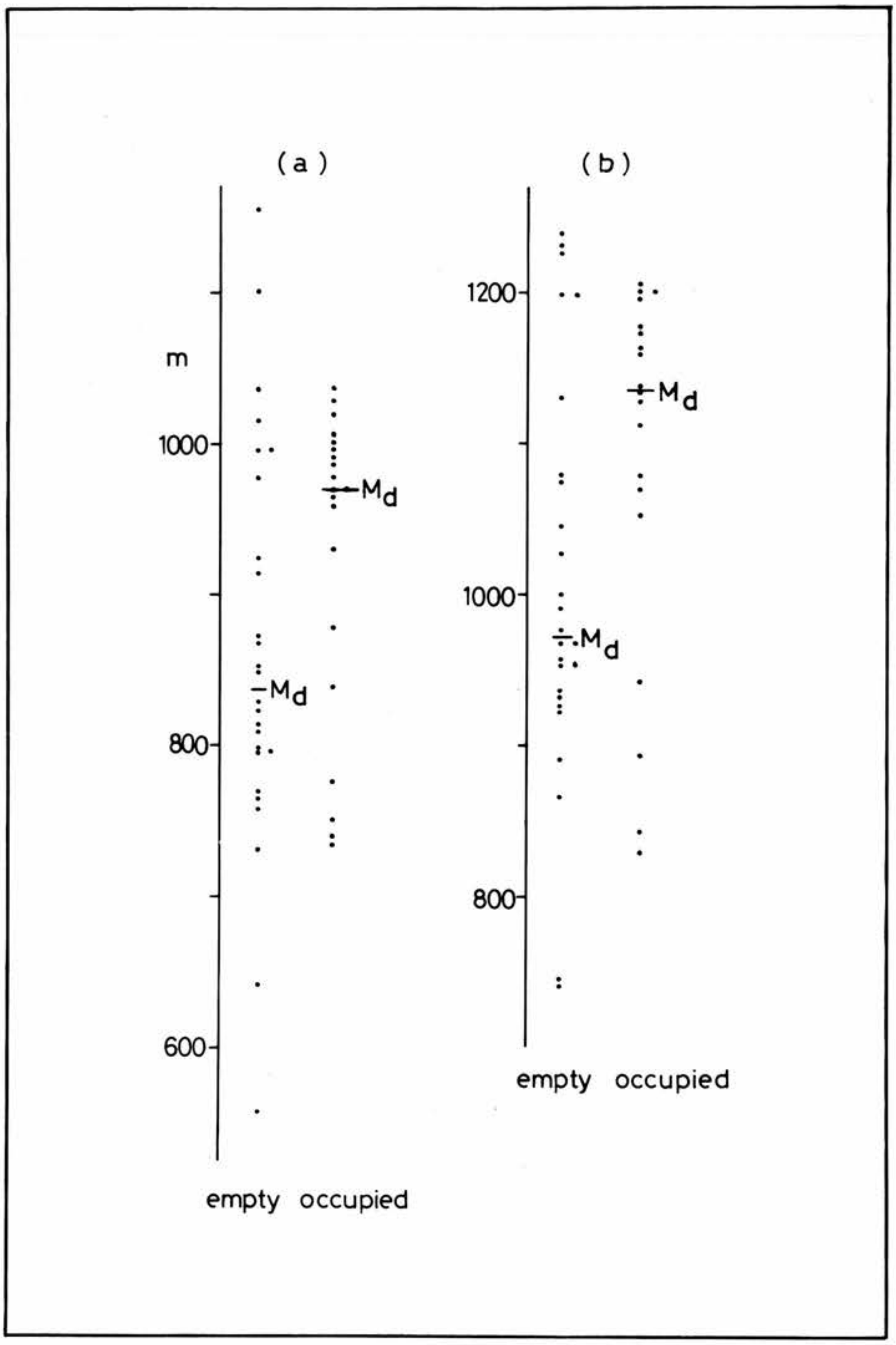


Fig. 9.4 Altitude of Glacierized and Empty Source Areas in the Cairngorms (a) base altitudes, (b) crest altitudes

However, since there are some rock walls lying below 800m that contained ice and some above 1000m that did not, simple altitudinal temperature and precipitation variations are not the only cause of glacierization of source areas during the Loch Lomond Stadial.

The second part of Table 9.3 relates to factors outside the source area that were found earlier to influence the site and altitude of rock walls. The table shows that glacierized source areas have significantly larger plateaux to their SW and southern sides but not to the SE. The same test was carried out on plateau size regardless of its direction and this also showed no significant difference between occupied and empty sites. The effect of plateaux is to encourage greater accumulation through snow-blowing and clearly the larger the plateau the more snow may be accumumlated. However, the lack of significance in the values for total plateau area while plateaux to south and SW are larger at sites occupied in the Loch Lomond Stadial suggests the importance of plateau direction and hence indicates the wind direction that distributed snow.

Table 9.4 Aspect of Occupied and Unoccupied Source Areas

Aspect	% of each aspect occupied during during Loch Lomond Advance
N	61.8
NE	48.9
E	52.4
SE	65.4
S	62.0
SW	0.0
W	28.6
NW	66.2

A variable related to plateau area is the aspect of the source area. Table 9.4 shows the nunber of glacierized and unoccupied source areas in each aspect class. A Chi-square test carried out on the individual point aspects showed that there is a significant difference in the orientation distributions of glacierized and non-glacierized source areas. A Chi-square value of 32.72 with 6 degrees of freedom was significant at the 0.001 level. Fig. 9.3 shows the variation in the distributions. While roughly half of the NE- and east-facing source wall segments were glacierized, two-thirds of those facing NW and less than one-third of those facing west were occupied.

The Relationship between the Equilibrium Firn Line and Rock Wall Altitude

In earlier chapters it was inferred that the altitude of the base of rock walls is related to the deterioration of climate at the onset of glacierization. It might therefore be expected that as glacierization proceded the final equilibrium firn line would lie below the rock wall. However, where the glacier limit is close to or within the source area, the firn line should lie above or close to the rock wall base altitude. In locations with high accumulation the firn line should tend to be below the source altitude and in locations such as found in much of the Cairngorms, where glacierization in the Loch Lomond Advance was marginal, the reverse should occur.

The relationship between the equilibrium firn line altitude and rock wall base altitude varies within the Cairngorms. On 9 of the 16 glaciers with sources against rock walls the estimated equilibrium firn line (Sissons, 1979b) lies 36-60m above the rock wall base. For 5 they lie within 30m of each other and on the remaining 2 the equilibrium firn line was over 100m below the rock wall base (Fig.9.5a). The two latter glaciers occurred in the southwestern Cairngorms where ice from several sources coalesced and they were the two largest cirque glaciers (Fig. 9.1). The rock wall base lies 17m above the equilibrium firn line in Coire an t-Saighdeir, a source area on the SE side of Cairn Toul and is 26m higher in the large Garbh Coire at the head of Slochd Mor.

From the above observations it is postulated that the relationship between equilibrium firn line altitudes and rock wall base altitudes is influenced by both the location and size of the source area. However, since in over half of the source areas the relationship between firn line and base altitude is very similar, the influence exerted by site and size is complex. The relationship may be explained by considering several factors involved in the association between a glacier and its source wall. In order to travel beyond its source area the glacier must have:

(1) sufficient accumulation so that the net balance is positive;

(2) sufficient time to expand;

(3) be located where it will not be inundated by external ice; and

(4) not be disadvantaged in terms of exposure outside the protective rock wall area.

The first three considerations are related since the time factor varies with the rate of accumulation. Within the small area of the Cairngorms it is assumed that the length of glacierization during the Loch Lomond Advance did not vary. The important factor is the differential rate of accumulation. With winds generally from the south or SW the largest precipitation occurred in the south and central Cairngorms, with the totals for glaciers with large plateaux to their SW further increased by blown snow.

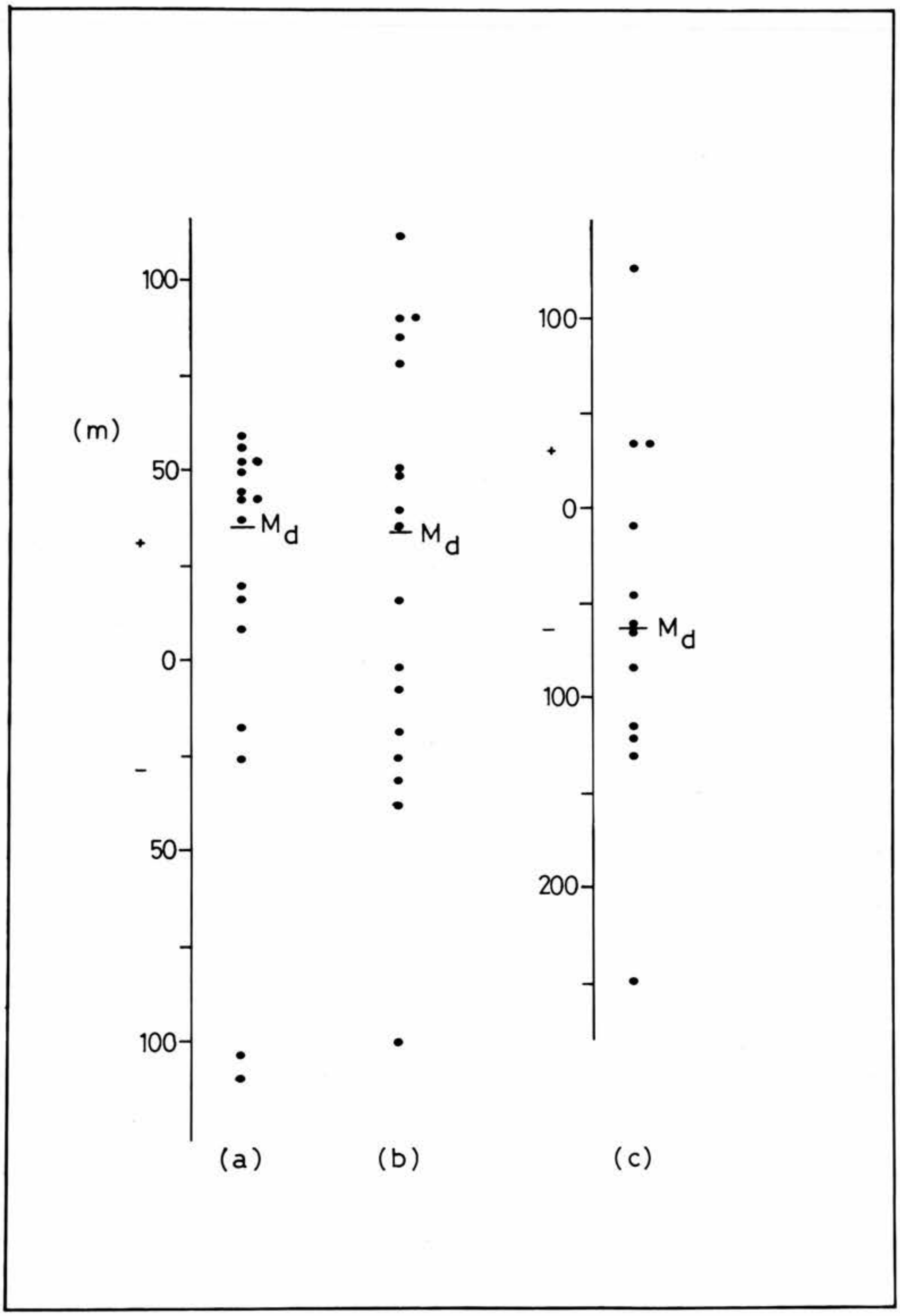


Fig. 9.5 Equilibrium Firn Line minus Rock Wall Base Altitude
(a) Cairngorms, (b) SE Grampians, (c) Cuillins, Skye

Location was also important in the siting of source areas relative to each other. Where the ablation zones of glaciers coalesced and convergence took place into confined valley floors such as Slochd Mor, and the glaciers were fed by two or more accumulation zones, the likelihood of a glacier terminating far below the source wall bases was enhanced. This factor is illustrated by the glacier formed in the source areas of Garbh Coire and Lochan Uaine Coire, which is composed of four source walls with one convergent glacier whose equilibrium firn line lies 104m below the mean rock wall base altitude. Parts of the accumulation area of this glacier were also in the lee of plateaux from all directions between NW and SE through south. This multiple source area lies at the same altitude and same type of site as its neighbour Coire an t-Saighdeir which has only one source wall but contained a glacier with an equilibrium firn line just below the rock wall base. The necessity for accumulation to be sufficent through precipitation as well as coalescence is exhibited by Coire a'Chlioch and Coire nan Clach which were occupied by a coalescent glacier (Fig. 9.1; Sissons, 1979b) that did not travel beyond the protective source walls. Its equilibrium firn line altitude is 53m above the mean rock wall base altitude.

The fourth factor above concerns exposure to solar radiation outside the area shaded by rock walls as well as loss through drifting off exposed ice surfaces. In Chapter 8 the insolation model was used to calculate incoming short-wave radiation received along the centre line of Coire an Lochain. It showed that close to the walls themselves shade is considerable, but diminishes rapidly outwards. In the ablation zones of glaciers that have low albedos and that are not protected by side walls this would be significant. Similarly, beyond the protection of the enclosed cirque, exposure to wind is increased. Derbyshire and Blackmore (1974) reported an overall reduction in windspeed of 50-70% within a cirque in SW Ireland compared to neighbouring free airflow. In view of the importance of wind-drift into lee source wall locations it is likely that snow blown by wind off the exposed parts of glaciers would also have some effect on glacier net balance.

These factors apparently combined in the Cairngorms in such a way as to permit extensive growth of a glacier beyond its protected local environment only if the positive factors of accumulation through precipitation (location on southern side of massif), wind drift (location on northern and northeastern side of plateaux) and high accumulation (coalescence of more than one source) were large enough to overcome the predominant powerful negative net budget outside the source areas themselves. At most of the Cairngorm source areas this was not the case; glaciers were able to exist only in the favourable local climate for which, through previous source wall erosion, they were themselves partly responsible.

The containment of glaciers within their source areas is characteristic of the Cairngorm region in the Loch Lomond Stadial. It is possible that other areas exhibited a different relationship between equilibrium firn line and glacier source wall base altitudes. To investigate this two more areas that had discrete and convergent source wall glaciers during the Loch Lomond Stadial were studied, these being the Cuillins of Skye and the SE Grampians. The trend surface altitude of equilibrium firn lines across the Highlands during the Loch Lomond Stadial was very low on Skye (Sissons, 1980) and rose steeply from the Highland Boundary across the SE Grampians and Cairngorms. Skye was apparently the most advantaged region of the field area; hence it should display the lowest firn line minus source wall values, while the SE Grampians values should lie between those of Skye and the Cairngorms. Estimates of equilibrium firn line altitudes by Sissons (1977) and Sissons and Sutherland (1976) were employed for Skye and the SE Grampians respectively.

Fig. 9.5 shows the values for equilibrium firn line minus rock wall base altitude for each region and these are plotted in Fig 9.6. Linear regression lines are drawn through the points for each region. Analysis of covariance between the firn line altitude and rock wall base altitude, taking into account the variation due to location, indicates that the three regressions may be considered statistically to have the same slope. The location of the slope with reference to the 45^{o} slope of equality is qualitatively important since it shows the probable areal differences in the relative altitudes of the firn line and rock wall base altitudes. On Skye, at all altitudes, firn lines tend to lie below rock wall base altitudes, while in the Cairngorms rock wall altitudes tend to be just above firn line altitudes. However, in the SE Grampians at low altitudes the firn line tends to lie above the rock wall base and at higher altitudes the tendency is reversed.

Discussion

Altitude can only partly explain why some potential glacier source areas in the Cairngorms were occupied by Loch Lomond Advance glaciers and that others were not. The analyses carried out above may aid the explanation. Firstly, almost all the rock walls in the eastern Cairngorms were occupied during the Loch Lomond Stadial while fewer nourished glaciers farther west. Secondly, there is a strong correlation between those rock walls that were occupied by Loch Lomond Advance glaciers and the location of plateaux above their southern and southwestern edges. Thirdly, in the Cairngorms the equilibrium firn line altitudes of Loch Lomond glaciers were generally higher than those of the rock wall base altitudes and most glaciers remained confined by their source walls. On the Cuillins in contrast an area well-placed to receive precipitation from an Atlantic source, neither of the last two correlations was often found.

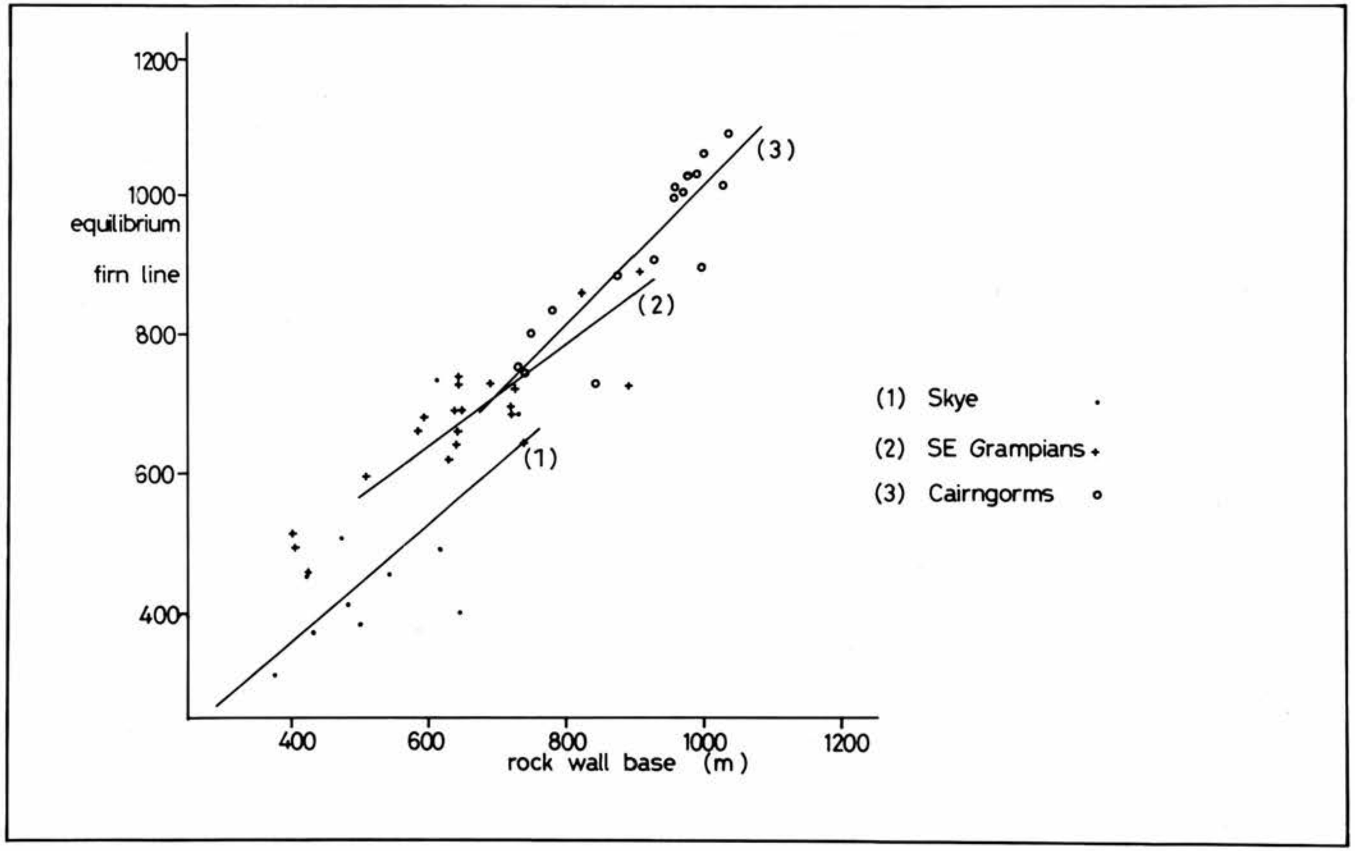


Fig. 9.6 Equilibrium Firn Line and Rock Wall Base Altitude in the Cuillins, SE Grampians, and Cairngorms

The first result initially appears difficult to reconcile with the evidence given by Sissons (1979c), who found that within the Cairngorms the greatest area of ice at the Stadial maximum was in the west and central mountains. These are also the areas that have been deeply gouged during many occupations by ice to form troughs and glacial breaches such as Gleann Einich and the Lairig Ghru. Also Fig. 9.1 shows that the majority of potential source areas occur in the western Cairngorms. This indicates that generally during glaciation this part of the Cairngorms was most severely glaciated. The correlation between the nourishment of glaciers and plateau areas indicates the importance of windblown snow to the process of accumulation particularly in the eastern Cairngorms where the largest tracts of upland plateau occur. Most rock walls in the eastern Cairngorms nourished glaciers, in contrast to farther west where rock walls lie beneath smaller upland areas. It is again inferred that precipitation in the eastern Cairngorms was always low during glaciation and that only glaciers supplied by much wind-blown snow could exist in any partial glaciation. The particularly rapid decrease in precipitation eastwards across the Cairngorms and the existence of empty source areas in the western Cairngorms during the Advance indicates that the climate has not always been so dry during glacierization.

The comparative study between the Cairngorms and Skye showed that, by contrast, the glaciers of Skye were not necessarily confined to their rock wall basins and that firn lines were generally lower than rock wall base altitudes. There is no reason to suppose that the possibly drier climate of the Cairngorms during the Stadial was not matched in the west of the study area.

Problems that now arise are (i) why the Loch Lomond Stadial climate was relatively dry in the northeastern Scottish Highlands when the volume of ice that built-up in the western

Highlands and islands at the same time was very large, and (ii) what conditions would be favourable for glacierization of the Cairngorms? Understanding of these problems requires consideration of the Loch Lomond Advance in terms of the environment immediately preceding and during it.

At the maximum southern extent of polar waters during the Loch Lomond Stadial the sharply defined polar front in the Atlantic Ocean lay at the latitude of SE Ireland (Ruddiman et al., 1977). The northern British Isles was therefore surrounded by very cold water and the North Sea would have been frozen over for much of the year possibly from early in the Stadial. This would have caused very little moisture from this source precipitated on the eastern Highlands, in contrast with the present, when northerly and easterly airstreams contribute significantly to winter snowfall in this area.

Depressions that form in the broad zone between polar and sub-tropical waters at present tend to follow one of two tracks, moving across the British Isles and turning NE towards Scandinavia, or moving across the southern British Isles towards France. With the movement of the polar front southwards, squeezing the broad mixing zone between the water masses the depression tracks would also have moved south and would have followed a more narrowly defined track. Present depressions that track across the southern British Isles tend to produce southeasterly winds in advance of the warm or occluded front over northeastern Scotland (Hay, 1949). During the Loch Lomond Stadial a southerly displacment of depression tracks would have tended to make conditions less favourable for glacier development in the Cairngorms. In accord with this inference, most of the unoccupied source areas in the Cairngorms at that time were on the northwestern side of the upland mass.

Although the Scandinavian ice-sheet was largely in retreat during the Loch Lomond Advance in Scotland, with only a slight oscillation on its southwestern margin (Mangerud, 1980), an atmospheric winter high pressure cell was still maintained over it (Lamb and Woodroofe, 1970). Many depressions travelling eastwards across the Atlantic would have been deflected to a southeasterly track and slowed down in their passage. This would have severely limited precipitation in northeastern Scotland while possibly increasing it in the west and SW.

As a corollary to these arguments an environment that would have favoured the development of rock wall glaciers in the northeastern British Isles to a greater extent than during the Loch Lomond Advance would have had a greater proportion of snowfall arriving from easterly and northerly directions. Additionally, the North Sea would not have been seasonally frozen over nor would there have been a strong winter blocking high pressure system located over Scandinavia. These conditions would most likely have occurred at the onset of glacierization following a full interglacial rather than a short amelioration. At that time eustatic sea-level would have been at its highest and the ocean adjacent to the northern British Isles would have initially not been very cold. Without a large ice mass over Scandinavia winter atmospheric blocking systems would have deflected depressions far to the south much less frequently. On the contrary, depressions following tracks across southern England would have resulted in SE to east winds over the eastern part of the British Isles with the advantage of additional moisture being absorbed over the open North Sea. Also, depressions arriving from the NW and north, as with polar lows of the present day, would have been capable of bringing large amounts of snowfall to the exposed northern Highland margins such as the Cairngorms. Hence, it is postulated that the northeastern British Isles would have received its greatest snowfall at the onset of glacierization following an interglacial or period of little ice over Scandinavia. As ice build-up proceeded in Scotland this area would have progressively experienced a relative decline in mean winter precipitation particularly in view of the topographic barriers to precipitation in the northeastern Highlands and the effect of cooling of the lowest atmospheric layers following the passage of air across the ice-covered Western Highlands.

The timing of the erosion of the cirques in the Cairngorms has been discussed by several authors. Sugden (1969) hypothesised that there were three stages of cirque formation corresponding to various modes of size and elevation. Clapperton and Sugden (1977) did not defend this view but rather postulated that the cirques were partly eroded in marginal conditions which may have occurred at several times during the Devensian and were modified by the Late-Devensian ice-sheet. From the evidence presented here it is suggested that while some rock walls were eroded in each period of climatic deterioration at the onset of each glacial phase, the rock walls of the Cairngorms were most actively eroded during the short periods when glacierization occurred following interglacial conditions or else when the Scandinavian ice-sheet was of limited extent.

Conclusions

1. When considering the erosion of highland ice source locations during partial glaciations the study of cirques fails to increase significantly the information gained from studying rock walls alone.

2. Glacier source walls tend to be steeper than cirque back walls and have a more restricted aspect distribution. This indicates that glaciers formed against the rock walls rather

than the walls facing other directions in cirques and confirms the suggestion in Chapter 2 that it is more useful to study source walls than cirques. In the Cairngorms non-rock wall portions of cirque headwalls tend to be extended from rock walls to face between north and west generally.

3. Analysis of cirque shape reveals that morphometric ratios are largely related to local topography. The length/depth ratio is particularly dependent on the location of the cirque within the mountain mass.

4. Treating the population of former glacier source walls as the probable sources for independent mountain glaciers during partial glaciations allows study of the last occupation of the source areas in relation to the occupation over numerous events. In the Cairngorms only 2 glaciers of Loch Lomond Advance age were not nourished beneath true source walls.

5. The location of glaciers in comparison to the total number of potential source sites in the Cairngorms during the Loch Lomond Stadial again indicates the lack of precipitation during the glaciation of this area. The Stadial may have been even drier than during some previous glaciations. This is attributable to the occurrence of the Loch Lomond Advance while the Laurentide and Scandinavian ice-sheets still existed and world sea-level was low. The southern North Sea was therefore dry land at the outset of the stadial and the northern North Sea was frozen over for much of the year.

6. Conditions favouring the partial glaciation of the northeastern part of the British Isles would have occurred when the sea areas to the north and east could contribute moisture to winter precipitation. Such conditions would have prevailed at the termination of an interglacial or when the area covered by ice in the northern hemisphere, particularly Scandinavia, was at a minimum.

CHAPTER 10

CONCLUSIONS

Introduction

The results of this research study are summarised in three parts: the first concerns the way in which rock walls are glacierized and eroded in terms of both regional and local distributions; the second relates the characteristics of rock walls to the climatic environment during the build-up stage of glacial phases; and the third concerns the periods when this erosion occurred.

Glacierization and Erosion of Highland Ice Source Areas

The distribution of rock walls across the study area, their altitudes and their azimuths, are used to infer the conditions under which their glacierization and erosion occurred. The study has shown that rock walls have a highly clustered distribution throughout the study area. On the mainland they occur most frequently in parts of the West Highland and SW Grampian regions, but they are relatively scarce in the Monadhliath Mts and in the north and east. The mean rock wall base altitude tends to rise in the opposite directions. In the West Highlands and SW Grampians rock walls are common far below 600m but they rise towards the north and east, occurring above 1000m in the Cairngorms.

Rock walls are generally largest in area and depth in the Cairngorms and on Skye although some large forms are found in the SW Grampians. By contrast rock walls in the West Highlands are sometimes well developed in amplitude but rarely in area.

Azimuthally, rock walls are highly clustered. Across the entire study area the distribution of rock wall mid-point aspects is concentrated in the NE quadrant. However, this masks an increasingly easterly component of direction from west to east and variations in the degree of clustering.

In Chapter 3 it was considered that the distribution of rock walls is particularly associated with the distribution of precipitation across the field area. It was postulated that the rock wall density pattern could be partially explained by a precipitation pattern that decreases inland from a maximum at the highland margins in the west and SE and enhanced by the distribution of upland in the study area. In Chapter 6 trend surface analysis was used to show that a close relationship also exists between rock wall altitude and the proposed precipitation pattern.

Taken together the individual observations noted above produce several groups of characteristics all of which cannot be attributed solely to the relationship between precipitation rates and glacierization. Firstly, rock walls that occur in neighbourhoods of high densities at low altitudes may have quite different magnitude and aspect characteristics. They are either well developed amplitudinally and areally with a lower than average aspect clustering, or they are poorly developed areally and display a more highly clustered azimuthal distribution. The former characteristics are those that might be expected if the precipitation pattern were the sole factor controlling the erosion of rock walls. The latter characteristics are evidence that other factors are influential.

Secondly, rock walls with large amplitudes and areas occur not only at low altitudes in areas of high density but also are characteristic of some rock walls where densities are low and altitudes high. This combination of characteristics is inexplicable in terms of the precipitation pattern alone. The precipitation model also does not explain the scarcity of rock walls in the south of the West Highlands region, where precipitation is, and probably was, amongst the highest in the study area.

These occurrences can be explained by a model of glacierization that relates the speed of deterioration of climate, the lowering of the snowline and the rate of build-up of ice masses in different parts of the Highlands. It is proposed that in any climatic deterioration glacierization was initially controlled by precipitation and accumulation rates. However, in rapid climatic deterioration, where the net accumulation rate was high, where the snowline fell quickly and where the topography was not an obstruction to ice movement, glacierization of the whole land surface was rapid and rock wall sites were not eroded. But, where all these conditions were not fulfilled glacierization proceeded to a variety of equilibrium forms through the accumulation of ice beneath rock walls, the coalescence and the convergence of ice from these sites, and the formation of valley ice-streams, piedmont glaciers and ice caps. This set of processes produced a variety of erosional end products in the form of rock walls, depending on the rapidity of glacierization, the influence of submergence under large ice bodies and the effect of encroaching ice from external sources.

Elsewhere, the rapidity of snowline lowering has been envoked to account for glaciated highland landscapes with few cirque sources. Ives et al. (1975) suggested that in plateau areas, the snowline could be lowered rapidly to the altitude of much of the land surface. On this hypothesis the whole area would have been glacierized synchronously rather than a few sites being selectively eroded. The final outcome would thus resemble that proposed above in which rock walls would not be formed.

In Chapter 3 it was considered that the southern part of the West Highland region was glacierized in this rapid fashion for two reasons. Firstly, it is extremely unlikely that the area experienced a scarcity of precipitation while neighbouring areas were evidently heavily glaciated. Secondly, this mid-latitude and maritime location represents the situation in which rapid glacierization is most likely to have occurred. This is because rapid snowline lowering is only probable in areas where accumulation can increase rapidly relative to ablation. This would have been most probable in areas of high precipitation where regional ablation characteristics are relatively uniform.

However, the present topography does not conform to the ideal pattern of the rapid glacierization model although it has fewer high peaks and ridges than neighbouring regions. In this terrain some high altitude rock walls might be expected even with rapid glacierization. Rapid snowline lowering *per se* is not of great significance. Nonetheless, rapid glacierization leads to the differential build up of ice between different areas at both a local valley scale and regionally. The influence of the build-up of ice outside the rock wall source area has seldom been emphasised. It is considered here that both locally and regionally derived external ice bodies greatly affected the erosion of rock walls.

Regionally, the importance of external ice is displayed in the southern West Highland region. With ice build-up greatest in the West Highlands and the SE Grampians and with the migration of the ice-shed eastwards with time, ice moving west from the latter area contributed to inundate the former area, while farther north the lower precipitation over the Monadhliath plateau meant less external ice streams over that part of the W Highlands.

Locally external ice affected the distribution and altitude of rock walls in much of the study area. Rock wall altitudes are related largely to the depression of the snowline just below summit altitude, so that to some extent rock wall base altitude is related to mountain summit elevation. As the snowline declined farther a stepped series of rock walls might have been expected (e.g. Miller, 1961, 1975) but was seldom found. This is attributed to the dynamic nature of glacierization whereby rock wall (cirque), valley, piedmont and ice cap glaciers are formed simultaneously where net accumulation rates are high. For example, in a valley whose sides are occupied by rock wall glaciers that were initiated when the snowline was just below summit altitude, a valley glacier may also exist. As glacierization continues the valley glacier grows through the convergence of several ice streams and may overwhelm the smaller rock wall glaciers which may then cease to erode their beds.

External ice also affects the azimuthal distribution pattern of rock walls. Since the first rock wall glaciers are initiated when the snowline is just below the summits of the mountains, no matter how favourable the whole region is to glacierization the initial rock walls are always formed at relatively high altitudes and in favourable azimuths. Thus in certain favoured mountainous regions where ice streams grow rapidly, far from expecting well-developed rock walls at low altitudes and with a variety of azimuths, the reverse is the case: rock walls occur close to the summit altitudes, still have a clustered distribution related to the early period of marginal suitability to glacierization and are poorly developed in depth because periods of rock wall erosion have been limited. This appears to be the case in the northern part of the West Highlands region.

However, in location where external ice does not affect rock wall formation, stepped features might be more likely. The only well developed stepped ice source in the study area occurs at such a site, on Skye. Also, in contrast to the neighbouring mainland, the azimuthal distribution is varied and the Cuillins contain some of the largest rock walls in the field area. The Cairngorms is another region of minimal external ice interference and rock walls are large in comparison with nearby.

The final factor, submergence beneath large ice bodies, relates the importance of locally and regionally derived ice to the stage of glacierization reached and the rate of snowline lowering. It is presumed that specific rock wall erosion is prevented. However, where submergence was due to local ice it is inferred that the area was favoured for net snow accumulation, and early in the glacierization glaciers were nurtured below rock walls. Hence on the present landscape rock walls should be frequent but they would have small dimensions indicative of the short periods of active formation.

Conversely, where submergence was due to external ice, implying that local conditions were not conducive to glacier survival few rock walls occur, but they may vary in size and be azimuthally clustered. The former type of submergence may have occurred in parts of the northern West Highland region while the latter would be typified by the Monadhliath region.

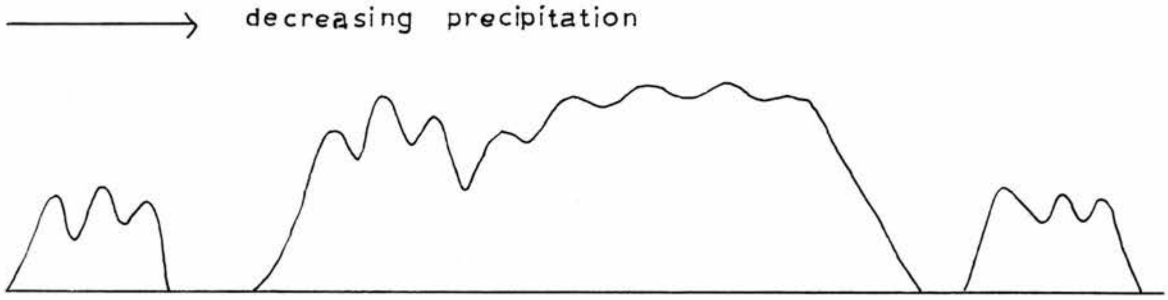
Clearly each of the factors contributing to the glacierization model vary in their relative importance both areally and over time. The model has been presented above in spatial terms rather than temporally although it is basically dynamic in nature. For any location, however, a temporal sequence has occurred through some part of the model during each period of glaciation. Nonetheless, the model is more helpful spatially since the same pattern is likely to have occurred with the same erosional result over many glaciations. If this were not so, the landscape would exhibit less order than has been indicated by rock wall morphometry.

Spatially, the model of glacierization explains why rock walls occur with so many conflicting sets of morphometric characteristics. Using the model certain type areas, dependent on location, the precipitation pattern and the surface topography can be identified. Fig. 10.1 shows an idealised pattern and varying topography. Six characteristic type areas are defined, all but one of which occurs in the study area.

The model of glacierization of rock walls highlights the problem of the preference of glaciers for sites previously occupied, since these sites, through former rock wall erosion, have added advantages of steep cliffs sheltering accumulated snow from further drifting, and protecting it from ablation. The rock wall site is thus suited to net accumulation earlier than the neighbouring hill slope, and thus slight variations in climate between glacierizations may not be sufficient to initiate glaciers in different sites. The lack of response in location of glacier sources to the dynamic environment means that rock wall sites are indicative of only the average climatic conditions at the onset of glacierization and there is little foundation for the common statement that cirque stairways and altitudes indicate the age of the feature (Miller, 1961, 1975; Godard, 1965; Sugden, 1969).

The glacierization model suggested here is contrary to the postulate that the lowest cirques indicate the altitudinal limit of glaciation (e.g. Svensson, 1959; Hastenrath, 1971). In terms of the model this would be invalid, not only in areas of rapid and heavy glacial build-up as Svensson argued, but also in areas where periods of cirque erosion have been uninterrupted by other ice streams, because glaciers might form when the microclimates of potential source areas became marginally suited to glacierization irrespective of the mesoscale climate. It is

Fig. 10.1 Model of Glacierization of Rock Walls



1 Windward islands	2a Windward coasts and highlands	3a Leeward mts plateaux	4 Leeward islands
no external ice, rapid snowline lowering; seldom submerged	rapid snowline lowering; synchronous glacierization; submergence	slow snowline lowering; occasional submergence; occasional influence of external ice	slow snowline lowering; very occasional submergence; very occasional influence of external ice
large features, variety of altitudes and azimuths	few rock walls, some high level, unclustered azimuths, poorly developed	few rock walls in topographically controlled sites, high altitudes, clustered distributions, large rock walls	little rock wall development
	2b Windward coasts, dissected relief	3b Leeward mts, more dissected relief	
	rapid snowline lowering, ice external to rock walls built up rapidly; submergence	slow snowline lowering occasional submergence occasional influence of external ice	
	many small forms, clustered azimuths range of altitudes	Few rock walls, small, clustered distributions	

fallacious to employ the lowest cirque level to indicate the lowest geological glacial equilibrium line because of the microclimatic effects of the site in depressing the local level of glaciation. Also, as glacierization continues the equilibrium firn line of each glacier may ultimately lie far below and beyond the initial rock wall floor. Instead, the altitude and site of rock walls indicate the nature and location of the initial glacierization.

The evidence presented here also suggests that it may be inaccurate to use reconstructed equilibrium firn lines that lie within rock wall boundaries to make inferences on the mesoscale climate of large regions. Where reconstructions are carried out on the basis of these glaciers alone one ought to be aware that the inferences are made from peculiarly glacial micro-environments.

The glacierization model explains the characteristic variations in rock wall dimensions across the study area in terms of climate and ice mass build-up. Locally amplitude varies with little regard to climatic variables. Rock type influences the amplitude of rock walls: the largest rock walls occur on igneous rocks and the smallest on Dalradian schists. Rock walls are best-developed on the gabbro of the Cuillin ridge which is however coincident with the area of most severe ice erosion by rock wall glaciers. It appears that, while certain rocks such as gabbros and granites can maintain large rock walls and others such as the Dalradian schists cannot, the predominant influences on amplitudinal variations at a regional scale are climatically induced. The independence of glacier sources from inundation by other ice sources, and the variation in glacier mass balance across the study area influence the amplitudinal development of rock walls to a far greater extent.

In the literature on cirques there has been much argument concerning the relative contributions of headward and downward erosion to the final shape (Embleton and King, 1975, p.239; McCall, 1960; Olyphant, 1977). The arguments relate to the differential rates of erosion between that of the rock wall by both glacial and periglacial action, and that of the floor by abrasion of the glacier along its bed. The model of rock wall glacierization is helpful in clearing the confusion. Two pieces of evidence support the view that backward erosion is faster than downward erosion. Firstly, the altitude of rock walls across the whole study area relates closely to summit altitude. This implies that there has been very little downward erosion, or that the summits have been eroded as quickly downwards as the rock walls. Secondly, in some regions the plateau areas are inversely related to the rock wall amplitudes showing that the rock walls grow in size at the expense of the plateaux.

In areas that are glacierized early and subsequently inundated with external ice from a valley source, downward erosion in a direction normal to the rock wall may be impeded but freeze-thaw action may continue on the exposed upper rock wall face. Hence upland plateaux may be quickly eroded while cirques do not increase in depth. Elsewhere, where inundation is less frequent, such as at high altitudes in the SW Highlands, both headward and downward erosion continued together. As a result very deep rock walls have been formed. In areas marginal to glacierization for much of the Devensian (at least) headwall erosion was faster than downward erosion, confirming the view that in the upper parts of cirque glaciers most debris emanates from the rock wall rather than from the floor.

The Climate during Partial Glacierization

The location, distribution and sites of rock walls in the field area may be used to derive information concerning the climate and average synoptic conditions that prevailed during periods of glacierization provided care is taken in relating these to how glaciation proceeded. Inferences are, however, qualitative rather than quantitative but are in broad agreement with those of Sissons (1980) derived for the Loch Lomond Stadial from Loch Lomond Advance glaciers. There are five separate lines of evidence related to rock walls that may be used to determine the climate during glaciation. These are the distribution of the walls, the trend in their altitudes, their relationship with upland plateaux, the direction in which those plateaux are oriented and the influence of insolation.

The distribution of rock walls is one of highest densities in the northern West Highland region and the SW Grampians, and low densities in the southern West Highlands, Monadhliath Mts and the eastern regions. Trend surface analysis of rock wall base altitudes indicated a rise in their level from west to east with a secondary SE to NW rise across the SE Grampians and Cairngorms. Large plateaux are rarely found upslope from rock walls in the western regions of the study area, but are very common in the east. Despite this, in the Loch Lomond Stadial the greatest glacial accumulations occurred in the west. In those areas where plateaux are found there is a significant correlation between rock wall altitude and the size of the plateau to the SW of the wall in preference to any other direction. The insolation model showed that shading by the rock walls of the floor area below a wall is very great but that 200m beyond a wall of average dimensions shading is insignificant. The model also showed that the surface gradients of the walls and the glaciers are important. In analysis of the factors causing azimuthal clustering of rock walls, the importance of plateaux for accumulation was found to be greater than protection from ablation.

From the distribution of rock walls, their relationship with upland plateaux and the trend in altitude of rock walls the general precipitation pattern across the Scottish Highlands was inferred, it having been postulated that the Atlantic Ocean was the only significant moisture source throughout periods of glaciation. It is inferred that precipitation would have decreased very rapidly indeed from west to east across the Highlands with a lesser trend decreasing from south to north over much of the study area and a more significant SE to NW decline across the SE Grampians, the Cairngorms and the Monadhliath Mts.

The precipitation that gave rise to this pattern would have been predominantly frontal, depressions being formed through atmospheric instability at the Atlantic Ocean polar frontal zone. As polar waters migrated southward the boundary between them and the sub-tropical Atlantic became more sharply defined (Ruddiman and Glover, 1975), causing frequent depressions to travel along more narrowly defined tracks than at present. Depressions arrived at the Scottish coast embedded in west to southwesterly airstreams and instability was subsequently increased by the forced uplift of air over the West Highlands. Precipitation would thus have been greatest close to the west coast; in the northern West Highlands where accumulation through precipitation and inundation by external ice masses was not overwhelming, the highest rock wall densities were found. Moving eastwards increasingly higher altitudes would have been required for the same amount of precipitation to fall; the trend surfaces indicate that this was so. The scarcity of moisture in the airstreams by the time they reached the Monadhliath region and the Cairngorms is indicated by the low densities of rock walls (that lie at high altitudes with large upslope plateaux) in these areas. The dryness of the atmosphere would have been exaggerated by two factors. Firstly, the airstreams passing over the western Highlands would be cooled by the large areas of snow and ice covered ground which would have forced moisture in the air to be precipitated at an early stage. Secondly, once a large ice body had built up over the western mountains, the surface topography would have been transformed so that on reaching the eastern plateaux forced uplift would have ceased and air might have begun to descend, increased stability making precipitation more unlikely. Both these factors suggest that as glaciation continued over many years the ability of eastern glaciers to accumulate snow declined relative to farther west (while ablation factors need not have varied spatially over time) and so the actual period of ice build-up in any partial glaciation was shortest in eastern parts of the country.

The south to north and SE to NW trends superimposed on the general west to east decline in precipitation were explained in terms of the dynamics of frontal activity. Precipitation, at its greatest immediately preceding the warm front, would have occurred largely before the winds veered from SE to SW (as commonly happens today). The lee slope of any mountain ridge during the passage of a front would therefore have been on its north to NW slope. In areas of high precipitation and few plateaux these would be the lee slopes on which rock wall glaciers would be expected. The West Highlands exhibits such a clustered azimuthal distribution about this direction in contrast to the wider azimuthal spread and increased easterly tendency farther east (although the alignment of topography is also important). Over large areas the direction of frontal winds would have encouraged a tendency for rock wall altitudes to rise from south to north as a response to decreased accumulation in the same direction. The sharp rise in altitude across the Highland Boundary has emphasised the importance of this, causing a rapid increase in precipitation where the air is forced to rise and a related decrease away from it to the NW. The locally high precipitation at the Highland Boundary is indicated by the anomolous south- to SE-facing rock walls in Glen Clova and Glen Isla.

Following the warm front and its accompanying snowfall winds would have veered rapidly to SW, and usually strengthened, so that in those areas where snow had fallen on upland plateaux it could still be transferred to sheltered NE-facing lee locations. This is substantiated by the differences between those areas with upslope plateaux and those without. In the west azimuths tend to cluster about north, but eastwards they alter to a NE to easterly mode. It is glaciers in the latter areas that would have benefitted most from the accumulation of wind-drifted snow, and indeed generally would have required this in order to be maintained. Because it is more difficult for drifting to occur once snow has lain, it appears that some snowfall arrived from westerly air flow as well as from frontal systems.

The synoptic pattern during the accumulation season has been inferred to have been one of frequent depressions that brought large quantities of precipitation to western areas, but which were relatively dry on reaching the eastern Highlands, over many periods of partial glaciation. In summer much of this precipitation may have fallen as rain, particularly at low altitudes in the west. The length of each ablation season at individual rock walls would therefore have varied, the longest ablation season being at the low level westerly sites and the shortest at the high level northeasterly ones. This indicates that an even greater precipitation gradient would have been required in winter in order to maintain the difference through the adverse ablation season. It was suggested therefore that the atmospheric circulation would have tended to be less vigorous in summer than in winter.

Summer anticylonic conditions would have been possible, although less likely than at present, giving clear sky conditions with sunny daylight hours. The lack of south-facing rock walls across much of the field area and the restriction of many of the Loch Lomond glaciers to the area beneath rock walls protected from insolation is indicative of this. The relative importance of the roles of wind-drifting and shading may have varied over time. Obviously, during the initial formation of rock walls protection from insolation through shading was not relevant to the siting of glaciers, but it has increased with their erosion. Conversely, with the erosion of rock walls by glaciers across upland plateaux, the importance of accumulation through wind-drifting would have declined. The statistical analysis has therefore emphasised the importance of plateaux in early glaciations while latterly these sites have become increasingly protected from insolation.

During periods of partial glaciation there were great climatic contrasts across the study area, from extremely snowy in the west and SW to increasingly dry and cold in the NE. In winter the average synoptic situation may be pictured as a depression with fronts lying across the area. Before the warm front winds were southeasterly but then veered rapidly to fresh southwesterlies. In summer depressions were fewer, interspersed with periods of low cloud or clear skies.

The Age of Rock Walls

Both the glacierization model and the inferred climate during rock wall erosion indicate that rock walls could only be formed at specific times when conditions were just severe enough for glacierization to occur. They were not necessarily eroded synchronously across the study area since at locations inundated by ice, erosion of rock walls ceased in preference to erosion parallel with the flow of ice streams in valleys or troughs. Thus rock walls in the West Highlands particularly were eroded for some time at the onset of each glacial period, but with the build-up of ice sheets erosion was curtailed. In less favourable areas initial accumulation was slower, more selective and erosion proceeded for a longer time at a slower rate until ice streams inundated valley side sites or nourishment ceased through starvation by progressively decreasing precipitation. The deterioration of climate from full interglacial conditions or when ice sheets where not extensive in Northern Europe aided the growth of glaciers and erosion of rock walls in these areas particularly.

Rates of cirque erosion have been calculated by several authors following the method outlined by Andrews (1972) who calculated a range of rates from 25 to 200mm$(1000yr)^{-1}$ on Baffin Island. Anderson (1977) calculated a range of 8 to 76mm$(1000yr)^{-1}$ also on Baffin Island. In contrast on the Arapaho Glacier in the Colorado Front Range, Reheis (1975) computed rates of 4920 to 8160mm$(1000yr)^{-1}$. These rates must be treated with scepticism since many factors, such as glacier size must affect the rate of erosion. However, if an average rate of erosion is assumed for glaciers in the study area the length of time required to erode them may be estimated. In the Cairngorms the median cirque area is 0.42km^2, which, using the formula 1/2.amplitude.area (Gordon, 1977), is equivalent to a volume of 0.033km^3. Assuming an erosion rate slightly less than that of the temperate Arapaho Glacier but much more than for Baffin Island, of, say, 2000mm$(1000yr)^{-1}$ some 40,000 years of continuous erosion would have been required. Since rates of erosion in the eastern part of the country were probably lower than these and rock walls in the west appear only to have been eroded for limited periods at the onset of glacierization, it is suggested that the rock walls of the study area have been actively eroded for varying lengths of time but for only a small portion of the Quaternary.

The oceanic sediment record indicates that oscillations from glacial to interstadial or interglacial periods occurred many times during the Quaternary (Ruddiman et al., 1977). During this time the rock walls of the study area were formed, eroded and modified. Evidence from the Devensian indicates several periods when rock wall erosion took place (Chapter 1). Fossil coleopteran assemblages from the Midlands and southern England show that there were at least two interstadials during the Devensian, one of which (Upton Warren) had summer temperatures as warm as today (Coope, 1975, 1977). Following this interstadial the climate became increasingly arctic and dry (Shotton, 1977). Fossil ice wedges have been found in southern England spanning the time from the deterioration after the Upton Warren Interstadial until the expansion of ice to the Late Devensian maximum (Williams, 1975).

The oceanic record has been consistently interpreted differently to this. Oceanic evidence from the Norwegian and Greenland Seas (Kellogg, 1976) shows that for a long period from the early Devensian the Norwegian Sea was seasonally ice-covered. At 82,000B.P. temperatures were as cold as at the maximum in 18,000B.P. (Kellogg, 1980) and airflow was similarly altered. This interpretation concurs with that of Ruddiman et al. (1980) who inferred from oceanic core evidence that a major glacial build-up occurred in temperate latitudes around 75,000B.P. Shackleton and Opdyke (1973) considered that there was no subsequent world-wide period of major deglaciation. Sutherland (1980) interpreted the unexplained high-level marine shell beds in Scotland that have minimum radiocarbon dates of 39,000B.P. as reflecting the build-up of the Scottish ice sheet at some time in the early Devensian. He considers that the evidence for extensive deglaciation of Scotland prior to

27,000B.P. is not strong since it relies on only two uncertain dated deposits.

If the view that Scotland was glaciated early and continuously in the Devensian is creditable the problems of timing of cirque erosion are diminished. If a body of ice of proportions not much less than that which pertained (in Scotland) at the maximum existed for some 60,000 years many of the smaller western cirques would have been submerged below the ice and could not have been continuously eroded, while those in less favoured areas were eroded slowly. This would have been particularly so if, as Kellogg (1980) suggested, airflow was northerly along the Norwegian coast as a result of ice in the Norwegian Sea. For much of the Devensian NE Scotland would thus have benefitted little from precipitation from northerly airstreams. Conversely, erosion of cirques in favourable mainland locations took place during the initiation of this ice sheet and the numerous cycles of glaciation that occurred throughout the Quaternary and that are recorded in the marine record.

It is concluded that this pattern of glacierization proceeded during the Devensian and many times before the last interglacial. In doing so, the present pattern of rock walls was produced on the landscape of the Scottish Highlands.

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APPENDIX 1 : ROCK WALL MORPHOMETRIC DATA

Key to Mid Point Aspects

Code	Orientation ° east of north
0	0
1	45
2	90
3	135
4	180
5	225
6	270
7	315

Geology Code : see Table 2.2 p.34

No	Crest Length (m)	Summit Altitude (m)	Mid point Grid Reference	Crest Alt. (m)	Base Alt. (m)	Width (m)	Amplitude (m)	Slope Angle (°)	Mid point Aspect	Geology
SE GRAMPIANS										
1	1200	820	32237893	729.2	575.4	242.3	153.8	32.4	1	5
2	950	1090	32237852	923.6	885.4	177.3	132.7	36.8	0	5
3	2850	1150	32307856	1034.0	921.0	154.3	113.0	36.2	0	5
4	2300	1150	32497855	1075.0	825.0	310.4	250.0	38.8	1	5
5	450	650	32867819	615.0	520.0	163.3	95.0	30.2	1	5
6	2400	800	33667800	684.8	598.0	169.2	86.8	27.2	1	3
7	2050	750	33847806	580.9	394.5	238.6	186.4	38.0	3	3
8	2000	850	32577783	760.5	615.2	193.8	145.2	36.8	0	5
9	1600	960	32067770	847.6	745.9	137.6	101.8	36.5	0	3
11	1350	860	33597749	783.3	641.3	194.0	142.0	36.2	4	10
12	900	870	33837739	711.0	586.0	186.0	125.0	33.9	4	10
13	2700	690	33927791	612.1	406.8	219.6	205.4	43.1	1	3
14	900	750	33937778	649.0	569.0	157.0	80.0	27.0	1	3
16	650	640	34337763	541.3	401.3	153.8	140.0	42.3	1	12
17	950	830	32977729	777.3	643.6	177.3	133.6	37.0	1	3
18	2300	900	32757745	730.0	507.9	281.3	222.1	38.3	2	3
19	550	940	32627737	851.4	721.4	182.9	130.0	35.4	0	12
20	2450	860	32527743	775.0	595.8	215.8	179.2	39.7	1	12
21	500	900	32137749	886.7	801.7	118.3	85.0	35.7	3	10
22	1100	880	32117774	786.7	586.7	333.3	200.0	31.0	5	12
26	600	660	34387837	604.3	538.6	98.6	65.7	33.7	3	12
27	950	660	34087829	464.5	358.2	145.5	106.4	36.2	2	3
28	700	880	32267777	856.3	781.3	131.3	75.0	29.7	1	10
30	950	930	32357806	866.4	771.8	110.0	94.5	40.7	2	5
31	3050	840	32467760	769.4	514.1	289.7	255.3	41.4	0	12
32	600	860	32357729	810.0	721.4	95.7	88.6	42.8	2	10
33	700	830	32307719	757.5	642.5	148.8	115.0	37.7	1	10
34	1500	870	33407754	783.8	640.0	186.9	143.8	37.6	4	3
35	1650	880	33297755	807.5	641.7	225.0	166.1	36.4	4	3

36	2400	880	33077757	779.2	599.2	241.6	180.0	36.7	3	3
37	3800	1010	31947806	862.6	707.4	171.5	155.1	42.1	0	12
38	600	960	32107801	897.1	795.7	127.1	101.4	38.6	7	5
40	700	900	34067877	701.3	631.3	103.8	70.0	34.0	1	5
41	500	670	34067827	610.0	511.7	128.3	98.3	37.5	2	12
42	450	1150	32437865	1023.3	888.3	176.7	135.0	37.4	0	5
44	1000	1050	30577767	944.5	863.6	114.5	80.9	35.2	1	3
45	2100	1050	30607758	972.3	873.6	133.6	98.6	36.4	2	3
46	350	950	30687794	860.0	784.0	128.0	76.0	30.7	1	2
47	650	1040	30447794	992.5	872.5	176.3	120.0	34.2	0	2
48	650	1030	30317779	877.5	763.8	157.5	113.8	35.8	0	2
49	400	720	30037738	694.0	612.0	100.0	82.0	39.4	2	12
50	1800	1130	29737746	1026.8	848.9	301.6	177.9	30.5	2	2
51	600	1130	29707733	1094.3	978.8	214.3	115.7	28.4	7	2
52	2100	1070	29517721	989.5	818.2	279.5	171.4	31.5	4	2
53	1800	900	28677752	829.5	704.2	179.5	125.3	34.9	2	1
55	500	710	31047875	666.7	600.0	150.0	66.7	24.0	2	3
56	1000	780	31827888	705.5	528.0	314.5	177.3	29.4	2	5
57	650	950	30537837	835.0	718.8	107.5	116.3	47.2	0	2
58	500	950	29747745	906.7	750.0	245.0	156.7	32.6	2	2
59	800	1100	29707742	915.6	780.0	261.1	135.6	27.4	0	2
60	700	770	29807817	721.3	613.8	176.3	107.5	31.4	2	1
61	1100	920	31237774	850.8	742.5	155.8	108.3	34.8	3	2
62	2500	1060	31807763	915.8	762.3	185.8	153.5	39.6	1	12
63	1100	960	31907772	900.0	722.5	201.7	177.5	41.4	4	12
64	800	800	30787698	683.3	620.0	106.7	63.3	30.7	1	12
116	1200	850	27667866	752.3	568.5	223.1	183.8	39.5	6	1
117	300	800	27617853	687.5	582.5	120.0	105.0	41.2	6	1
119	550	850	27197857	775.7	700.0	107.1	75.7	35.2	7	1
CAIRNGORMS										
65	1200	800	28717946	745.4	557.7	230.8	187.7	39.1	1	1
66	1650	980	28827994	995.6	750.6	173.9	145.0	39.8	0	1
67	400	950	28847946	926.0	766.0	220.0	160.0	36.0	4	1
68	400	920	28747922	890.0	796.0	118.0	94.0	38.5	0	1
69	650	730	28357905	647.5	537.5	138.8	110.0	38.4	7	1
314	900	1040	29037972	933.0	850.0	95.0	83.0	41.1	1	12

315	900	1090	29027981	1001.0	806.0	218.0	195.0	41.8	3	4
316	600	1100	29237978	968.6	872.9	112.9	95.7	40.3	0	4
317	1000	1260	29327985	1132.7	994.5	174.5	138.2	38.4	7	4
318	2750	1270	29527978	1177.2	987.2	219.7	190.0	40.9	0	4
320	1700	1280	29437989	1174.4	995.6	192.8	178.9	42.9	2	4
321	850	1240	29367996	1076.0	977.0	143.0	99.0	34.7	6	4
322	800	1260	29557976	1164.4	1001.1	208.9	163.3	38.0	2	4
323	950	1290	29637972	1202.7	1021.8	259.1	180.9	34.9	7	4
324	800	1290	29647972	1228.9	1100.0	236.7	128.9	28.6	2	4
325	1500	1290	29617966	1196.3	1029.4	218.8	166.9	37.3	2	4
326	350	1210	29687962	1080.0	928.0	208.0	152.0	36.2	2	4
327	550	1170	29697958	968.6	868.0	138.6	100.0	35.8	2	4
328	700	1310	29877989	1238.8	1153.8	110.0	85.0	37.7	6	4
329	1800	1160	29487927	1052.6	840.0	281.1	212.6	37.1	0	4
330	1000	1270	29438001	1160.0	1002.7	195.5	157.3	38.8	0	4
331	1050	1270	29488002	1197.5	1034.2	245.8	163.3	33.6	0	4
332	350	1190	29538010	1028.0	916.0	158.0	112.0	35.3	1	4
333	1050	1290	29568002	1197.5	995.8	365.0	201.7	28.9	1	4
334	900	1110	29078007	952.0	827.0	134.0	125.0	43.0	2	4
335	850	1100	29078003	953.0	758.0	205.0	195.0	43.6	2	4
336	1750	830	29088006	743.0	642.6	154.2	100.5	33.1	2	4
337	2050	1120	29047993	1045.5	799.1	332.7	246.4	36.5	2	4
338	1400	1300	29547999	1251.3	1036.0	224.0	215.3	43.9	3	4
339	550	1250	29647999	1130.0	1015.7	168.6	114.3	34.1	2	4
340	2000	1250	29997987	1162.4	977.1	217.1	185.2	40.5	2	4
341	1550	1160	30217984	955.3	824.1	178.8	131.2	36.3	2	4
342	1100	890	30257956	829.2	735.0	132.5	94.2	35.4	2	4
343	1000	1120	30026002	1071.8	930.0	177.3	141.8	38.7	2	4
344	1150	1100	30147996	976.2	852.3	137.7	123.8	42.0	2	4
345	850	1080	30248004	990.0	764.0	285.0	226.0	38.4	4	4
346	950	1030	30148065	924.5	812.7	180.9	111.8	31.7	6	4
347	900	970	30338066	864.0	730.0	184.0	134.0	36.1	7	4
348	3700	1150	31148012	1077.9	877.9	243.4	200.0	39.4	0	4
350	700	1080	31348031	935.0	796.3	167.5	138.8	39.6	6	4
351	1000	1080	31508033	942.7	777.3	222.7	165.5	30.0	7	4
352	600	970	31598027	842.9	737.1	182.9	105.7	38.8	2	4
353	2450	1200	30928004	1140.8	990.8	186.5	150.0	38.8	2	4
354	1100	1220	29858027	1163.0	961.5	263.8	191.5	37.3	7	4
355	2100	1180	30907990	1133.6	967.7	197.3	165.9	40.1	1	4
356	1100	1220	29968034	1132.0	962.3	219.4	169.7	32.8	7	4
357	1000	1180	30977982	1113.6	967.3	169.1	146.4	40.9	2	4

WEST HIGHLANDS

161	300	750	17878071	595.0	487.5	107.5	107.5	45.0	0	1
162	550	790	17958062	750.0	652.9	178.6	97.1	28.5	7	1
163	450	790	17968072	566.7	461.7	111.7	105.0	43.2	1	1
164	400	700	18108048	666.0	586.0	100.0	80.0	38.7	7	1
165	2250	1020	18178042	778.3	551.3	288.3	227.1	38.2	0	1
166	1150	1020	18268041	940.0	823.8	125.4	116.2	42.8	0	1
167	1900	1020	18288037	967.5	608.0	257.3	259.5	45.2	1	1
168	700	850	18398032	746.3	678.8	75.0	67.5	42.0	2	1
169	1250	880	19598088	847.1	713.6	217.9	133.6	31.5	0	1
170	500	890	19278051	851.7	766.7	116.7	85.0	36.1	1	1
171	800	900	19338041	754.4	686.7	93.3	67.8	36.0	1	1
172	350	810	19378038	730.0	674.0	82.0	56.0	34.3	1	1
173	400	810	19418037	780.0	616.0	222.0	164.0	36.5	0	1
174	850	1030	19938065	846.0	729.0	136.0	117.0	40.7	1	1
175	400	890	19992061	840.0	734.0	142.0	106.0	36.7	0	1
176	1000	1030	20358054	876.4	720.0	163.6	156.4	43.7	7	1
178	700	980	20328088	921.3	801.3	130.0	120.0	42.7	0	1
180	1350	1010	20328093	889.3	786.7	109.3	102.7	43.2	1	1
181	2150	1020	20208094	917.0	723.0	230.0	193.9	40.1	7	1
182	550	990	20468082	802.9	685.7	157.1	117.1	36.7	0	1
183	800	1020	20558091	974.4	832.2	172.2	142.2	39.6	2	1
184	1750	990	20518084	909.5	752.1	198.4	157.4	38.4	0	1
185	550	940	20608085	705.7	582.9	125.7	122.9	44.3	1	1
186	750	990	20708078	867.8	794.4	105.6	73.3	34.8	2	1
187	1000	990	20808082	836.4	706.4	156.4	130.0	39.7	5	1
188	600	990	20798084	927.1	838.6	118.6	88.6	36.8	0	1
189	600	990	20748088	880.0	751.4	178.6	128.6	35.8	1	1
190	550	730	19108126	584.3	460.0	157.1	124.3	38.3	7	1
191	350	950	20878087	874.0	796.0	98.0	78.0	38.5	0	1
192	250	950	20868079	887.5	780.0	102.5	107.5	46.4	1	1
193	250	950	20928076	820.0	685.0	170.0	135.0	38.5	2	1
194	350	1000	20088102	914.0	772.0	152.0	142.0	43.1	1	1
196	350	1010	20138100	844.0	764.0	90.0	80.0	41.6	0	1
198	600	1000	20208100	817.1	722.9	144.3	94.3	33.2	1	1
199	800	1000	20068105	891.1	731.1	175.4	160.0	42.3	1	1
200	300	1000	20438137	865.0	747.5	130.0	117.5	42.1	5	1
201	400	920	19768113	788.0	678.0	128.0	110.0	40.7	7	1
202	500	920	19858114	911.7	651.7	196.7	160.0	39.1	0	1

203	1100	900	19978113	815.8	609.2	255.0	206.7	39.0	7	1
204	550	910	19538123	870.0	690.0	157.1	180.0	48.9	0	1
205	400	940	19458114	924.0	834.0	94.0	90.0	43.8	1	1
206	400	940	19458117	814.0	730.0	118.0	84.0	35.4	1	1
207	950	1010	19408131	908.2	801.8	132.7	106.4	38.7	4	1
208	700	1010	19288128	930.0	715.0	282.5	215.0	37.3	3	1
209	600	940	19178124	707.1	625.7	122.9	81.4	33.5	7	1
210	1550	730	19058127	592.4	448.2	177.1	144.1	39.1	1	1
211	1250	1010	19278128	940.0	655.7	325.7	284.3	41.1	0	1
212	700	950	19368137	630.0	700.0	127.5	130.0	45.6	1	1
213	550	920	19458136	610.0	448.6	180.0	161.4	41.9	0	1
214	650	1010	19418131	882.5	761.3	128.8	121.3	43.3	0	1
215	850	840	19188142	686.0	568.0	141.0	118.0	39.9	1	1
216	1050	770	19248173	604.2	488.3	127.5	115.8	42.3	1	1
217	600	770	19178178	671.4	521.4	178.6	150.0	40.0	0	1
218	500	750	19378151	520.0	378.3	131.7	141.7	47.1	0	1
219	1750	930	19718179	795.3	587.9	232.6	207.4	41.7	1	1
220	600	1070	19768174	850.0	671.4	192.9	178.6	42.8	1	1
221	900	1070	19818167	957.0	756.0	237.0	201.0	40.3	0	1
222	600	990	19888166	885.7	664.3	244.3	221.4	42.2	0	1
223	1200	1030	19908150	940.8	756.2	186.9	184.6	44.6	7	1
224	300	980	19948149	900.0	735.0	140.0	165.0	49.7	0	1
225	800	700	18928134	603.3	428.9	271.1	174.4	32.8	0	1
226	800	710	18878126	548.9	377.8	228.9	171.1	36.8	6	1
227	1000	780	18768130	630.9	477.3	205.5	153.6	36.8	4	1
228	300	730	18508132	587.5	455.0	150.0	132.5	41.5	0	12
229	250	900	18468125	745.0	645.0	115.0	100.0	41.0	0	12
230	1050	970	18398130	868.3	711.7	195.0	156.7	38.8	0	12
231	1000	1000	21378165	905.5	740.0	187.3	165.5	41.5	3	1
232	500	950	21138157	876.7	748.3	135.0	128.3	43.5	0	1
233	1100	1050	21018174	961.7	826.7	175.8	135.0	37.5	1	1
234	300	1100	20868163	1025.0	907.5	117.5	117.5	45.0	2	1
235	800	1100	20968172	1033.3	924.4	138.9	108.9	38.1	0	1
236	1050	860	21498175	819.2	703.3	177.5	115.8	33.1	2	1
237	600	890	21768179	877.1	741.4	154.3	95.7	31.8	1	1
238	250	890	21718181	855.0	762.5	87.5	92.5	46.6	1	1
239	450	870	21838177	845.0	745.0	130.0	100.0	37.6	7	1
240	1050	1000	21398128	883.3	725.0	185.0	158.3	40.6	1	1
241	800	960	21468126	922.2	761.1	164.4	161.1	44.4	1	1
243	800	960	21558128	854.4	720.0	191.1	134.4	35.1	0	1
244	800	900	21608125	760.0	596.7	202.2	163.3	38.9	1	1

245	600	790	21988193	688.6	568.6	127.1	120.0	43.3	0	1
246	2500	780	21468082	672.7	490.0	209.2	182.7	41.1	0	1
247	500	740	18278157	563.3	405.0	188.3	158.3	40.1	0	1
248	1300	760	18368150	702.1	570.7	171.4	131.4	37.5	0	1
250	250	330	18618165	307.5	230.0	85.0	77.5	42.4	0	1
251	300	760	17977972	607.5	505.0	102.5	102.5	45.0	0	1
252	600	790	18017970	744.3	631.4	97.1	112.9	49.3	0	1
253	1250	790	18087968	735.7	869.3	225.0	166.4	36.5	1	1
254	900	720	18457972	670.0	523.0	152.0	147.0	44.0	7	1
255	1350	930	18537987	821.3	664.7	215.3	156.7	36.0	2	1
256	1300	1030	20298145	896.4	702.1	223.6	194.3	41.0	7	1
257	1750	1040	20378145	938.4	735.8	246.8	202.6	39.4	0	1
258	1000	1000	20478138	912.7	687.3	262.7	225.5	40.6	0	1
259	500	1000	20528139	906.7	671.7	325.0	235.0	35.9	0	1
260	500	990	20558143	861.7	693.3	218.3	168.3	37.6	7	1
261	1050	1030	20378055	930.0	820.8	124.2	109.2	41.3	1	1
262	1350	1030	20458051	954.7	842.0	141.3	112.7	38.6	0	1
263	900	1010	20508051	824.0	607.0	255.0	217.0	40.4	1	1
264	1050	980	20628046	885.0	802.5	93.3	82.5	41.5	7	1
265	800	1000	20638043	956.7	860.0	103.3	98.7	43.1	0	1
266	650	1000	20688039	896.7	792.5	143.8	103.8	35.8	1	1
267	350	890	20768049	726.0	628.0	132.0	98.0	36.6	1	1
268	1000	1000	20288184	929.1	803.6	182.7	125.5	34.5	0	1
269	1350	1030	20198189	976.7	867.3	170.7	109.3	32.6	1	1
270	1250	950	20068195	880.0	739.3	162.9	140.7	40.8	0	1
271	450	840	20368220	818.3	673.3	205.0	145.0	35.3	1	1
272	1700	1140	20458230	1005.0	807.8	330.6	197.2	30.8	0	1
273	550	1140	20508230	1052.9	934.3	135.7	118.6	41.1	7	1
274	850	1150	20598231	1009.0	919.0	105.0	90.0	40.6	7	1
275	500	1150	20578228	1108.3	1018.3	108.3	90.0	39.7	5	1
276	1100	980	20728225	902.5	791.7	155.0	110.8	35.6	0	1
277	1150	920	20828229	797.7	684.6	133.8	113.1	40.2	0	1
278	1200	920	20918222	800.0	657.7	178.5	142.3	38.6	1	1
279	900	1010	21228225	832.0	727.0	132.0	105.0	38.5	1	1
280	1350	1110	21118239	1036.0	894.7	188.7	141.3	36.8	2	1
281	1200	1030	21438246	963.1	803.8	220.0	159.2	35.9	0	1
282	400	1040	21558243	1002.0	872.0	132.0	130.0	44.6	1	1
283	400	1100	21098245	972.0	874.0	118.0	98.0	39.7	7	1

284	600	1010	21128249	1008.6	835.7	187.1	172.9	42.7	0	1
285	1150	1180	21278262	1130.8	995.4	151.5	135.4	41.8	4	1
286	600	1180	21238253	1125.7	1000.0	162.9	125.7	37.7	0	1
288	900	1180	21218264	1082.0	820.0	348.0	262.0	37.0	0	1
289	700	1100	21198271	861.3	701.3	228.8	160.0	35.0	1	1
290	600	1140	21378263	1117.1	1015.7	125.7	101.4	38.9	1	1
291	550	1130	21448264	1067.1	968.6	107.1	98.6	42.6	0	1
292	700	1050	21418275	892.5	733.8	168.8	158.8	43.3	1	1
293	1150	840	19448230	719.2	603.8	139.2	115.4	39.6	0	1
294	750	500	17417883	402.2	321.1	90.0	81.1	42.0	7	1
295	600	900	19557863	838.6	694.3	118.6	144.3	50.6	7	1
296	1100	990	20087877	870.0	738.3	195.0	131.7	35.4	0	1
297	1300	920	20197993	786.4	671.4	141.4	115.0	39.1	0	1
298	900	580	21687970	531.0	445.0	134.0	86.0	32.7	0	1
299	1000	900	22297962	805.5	679.1	166.4	126.4	37.2	1	12
300	600	900	22217958	857.1	764.3	151.4	92.9	31.5	0	1
301	1100	940	22207948	878.3	685.8	270.8	192.5	35.4	1	1
302	900	940	22237943	983.0	753.0	190.0	130.0	34.4	1	12
303	750	840	22347930	734.4	582.2	235.6	152.2	32.9	0	1
304	1100	910	22167924	795.0	515.0	348.3	280.0	38.8	1	12
305	700	910	22137921	863.8	696.3	252.5	167.5	33.6	0	1
306	1000	870	22067920	854.5	700.9	242.7	153.6	32.3	0	1
307	1250	770	21257859	707.1	565.7	158.6	141.4	41.7	1	1
308	1300	800	21357859	743.6	590.0	219.3	153.6	35.0	0	1
309	400	1080	21348123	966.0	842.0	144.0	124.0	40.7	3	1
310	850	1000	21208127	829.0	657.0	237.0	172.0	36.0	2	1
311	1250	1110	21218134	968.6	823.6	215.7	145.0	33.9	1	1
312	900	1040	21318149	942.0	830.0	149.0	112.0	36.9	2	1
313	700	520	17528035	467.5	305.0	221.3	162.5	36.3	1	1
478	700	560	18247507	511.3	431.3	108.8	80.0	36.3	6	5
479	500	610	18147503	578.3	436.7	191.7	141.7	36.5	1	5
484	1500	710	17417759	596.2	457.5	217.8	139.4	32.6	1	12
485	1000	710	17427753	560.9	400.0	252.7	163.6	34.1	2	12
486	2000	870	17857785	775.7	553.8	287.0	221.4	37.8	2	12
487	2200	870	17767778	788.3	530.0	382.7	258.3	31.6	7	12
511	1300	580	19497703	530.0	437.1	180.3	92.9	27.2	0	12
512	500	580	19637704	515.0	403.3	147.9	111.7	37.0	7	12
513	700	580	19817703	436.2	326.2	218.8	160.0	36.2	0	12
514	900	720	19087717	653.0	531.0	186.0	122.0	33.3	0	12

515	1500	880	19057629	781.2	492.0	342.2	289.2	40.2	1	12
516	800	730	19827653	648.9	529.7	191.7	119.2	32.5	2	12
517	2500	730	19697661	525.4	356.2	248.6	169.2	34.2	0	12
518	1100	660	18077765	440.0	265.0	226.0	175.0	37.7	2	12
519	2500	770	18747729	651.5	438.5	409.5	213.0	27.5	1	12
SW GRAMPIANS										
74	650	970	26097755	905.0	797.5	150.0	107.5	35.6	1	1
78	900	780	25637706	688.0	554.0	174.0	134.0	37.6	5	1
79	900	990	25997731	953.0	870.0	96.0	83.0	40.8	1	1
81	1550	770	25907790	601.8	454.7	177.6	147.1	39.6	7	1
83	650	810	25217773	707.5	596.3	146.3	111.3	37.3	2	1
84	300	850	25237739	767.5	642.5	150.0	125.0	39.8	1	1
85	900	1020	25187730	966.0	775.0	262.0	191.0	36.1	7	1
86	3500	1140	24957715	1075.8	837.5	300.8	238.3	38.4	2	1
87	1100	1070	25007731	960.0	852.5	128.3	107.5	40.0	1	1
88	2700	1170	24947729	957.1	677.5	363.6	279.6	37.6	7	1
89	750	1100	24817721	997.8	908.9	134.4	88.9	33.5	0	12
90	1800	1130	24627743	1067.4	957.9	151.1	109.5	35.9	0	12
91	1250	900	24637711	799.4	720.7	120.7	78.6	33.1	1	1
92	400	1080	24577734	974.0	880.0	106.0	86.0	39.1	1	12
93	2000	1100	24487735	1023.3	876.2	204.8	147.1	35.7	1	12
94	950	1020	24907744	971.8	686.4	374.5	285.5	37.3	3	1
95	300	1100	24807747	1077.5	1002.5	125.0	75.0	31.0	1	1
96	600	1090	24827750	940.0	800.0	190.0	140.0	36.4	2	1
97	550	1100	24807753	922.9	825.7	78.6	97.1	51.0	0	12
98	650	1080	24697758	903.8	821.3	120.0	82.5	34.5	0	1
99	1300	1100	24737751	1065.7	936.4	162.9	129.3	38.4	1	12
100	1600	1090	24727782	978.2	824.1	226.5	154.1	34.2	0	1
101	600	1010	24802784	974.3	881.4	131.4	92.9	35.2	2	1
102	700	960	24917795	825.0	683.8	175.0	141.3	38.9	1	12
103	500	830	24517757	753.3	666.7	108.3	86.7	38.7	0	1
104	1450	1020	25127708	893.8	709.4	240.6	184.4	37.5	3	1
106	800	950	25137700	750.0	553.3	224.4	196.7	41.2	3	1
107	1100	940	24157664	881.7	781.7	168.3	100.0	30.7	0	12
109	900	880	24467663	771.0	678.0	122.0	93.0	37.3	2	12
111	1300	870	24527645	772.9	644.3	187.1	128.6	34.5	1	5
112	950	810	24277633	693.6	596.4	154.5	97.3	32.2	2	1
113	650	810	24237645	780.0	681.3	152.5	98.8	32.9	2	12

114	1350	1020	25107820	970.7	882.7	119.3	88.0	36.4	0	12
115	250	900	25907822	827.5	765.0	112.5	62.5	29.1	3	1
121	900	1020	24907745	963.0	717.0	301.0	246.0	39.3	0	1
414	1400	1340	21577709	1062.7	849.3	278.7	213.3	37.4	5	12
415	800	1230	21577725	893.3	670.0	163.3	223.3	53.8	0	10
416	2700	1340	21617715	1218.6	891.4	340.0	327.1	43.7	0	10
417	1200	1340	21707711	1163.8	980.0	196.2	183.8	43.1	1	12
418	850	1340	21637711	1212.0	847.0	456.0	365.0	38.7	4	12
419	1000	1220	21777720	1130.9	996.4	186.4	134.5	35.8	3	6
420	1650	1220	21777723	1100.0	877.2	350.0	222.8	32.5	1	6
421	1300	1180	21747729	1070.0	882.9	284.3	187.1	33.4	1	6
422	1100	1180	21727734	994.2	877.5	165.8	116.7	35.1	1	6
423	1800	1240	21957718	1089.5	956.8	116.8	132.6	48.6	1	12
424	1100	1240	22007711	1123.3	980.8	145.8	142.5	44.3	2	3
425	2900	1240	21977717	1133.0	732.3	567.0	400.7	35.2	2	12
426	1300	1220	21937736	1133.6	868.6	347.9	265.0	37.3	1	6
427	800	970	22057704	924.4	764.4	213.3	160.0	36.9	2	2
428	900	1100	22297715	1012.0	765.0	323.0	247.0	37.4	2	12
429	700	1080	22347727	1041.3	948.8	140.0	92.5	33.5	3	2
430	900	1110	22387726	1056.0	949.0	165.0	107.0	33.0	0	2
431	1000	1100	22447723	1039.1	920.9	170.0	118.2	34.8	7	2
432	1600	1110	22367737	947.1	781.8	220.6	165.3	36.8	2	3
433	650	1010	22077741	905.0	580.0	543.8	325.0	30.9	2	3
434	300	1110	22407726	1080.0	1002.5	140.0	77.5	29.0	2	2
435	400	1110	22447727	1040.0	946.0	150.0	94.0	32.1	4	2
436	600	1100	22487729	1058.6	962.9	192.9	95.7	26.4	0	2
437	800	1180	22547735	1066.7	965.6	147.8	101.1	34.4	4	2
438	700	1180	22577736	1081.3	966.3	191.3	115.0	31.0	1	2
439	1500	1180	22647742	1086.9	868.1	301.9	218.8	35.9	2	3
440	1600	1120	22627745	1039.4	841.2	313.5	198.2	32.3	0	3
441	800	1040	22607756	924.4	813.3	124.4	111.1	41.8	3	12
442	400	960	22627759	846.0	770.0	90.0	76.0	40.2	1	12
443	800	930	23067721	912.2	736.7	195.6	175.6	41.9	2	3
444	1200	1120	23107731	1007.7	836.9	207.7	170.8	39.4	0	3
445	1350	1110	23187735	943.3	679.3	342.7	264.0	37.6	2	3
446	1000	1100	23247743	965.5	842.7	179.1	122.7	34.4	3	3

447	1500	980	23727733	931.9	795.0	159.4	136.9	40.7	2	3
448	700	960	23617739	903.8	818.8	107.5	85.0	38.3	1	3
453	1400	1050	23877846	956.7	775.3	242.0	181.3	36.8	1	12
456	1600	1050	22057653	999.3	866.4	210.7	132.9	32.2	0	12
457	1300	1060	22147655	985.7	807.1	267.1	178.6	33.8	1	12
458	1250	1130	22127664	998.6	882.1	167.1	116.4	34.9	2	12
459	300	1130	22157667	940.0	850.0	117.5	90.0	37.5	0	2
460	700	1010	22317660	938.8	861.3	122.5	77.5	32.3	6	2
461	600	1010	22317658	950.0	812.9	200.0	137.1	34.4	2	2
462	300	960	22217652	930.0	782.5	150.0	147.5	44.5	2	2
463	800	1050	22037648	957.8	861.1	132.2	96.7	36.2	2	2
464	1500	1030	21697652	930.6	810.0	186.3	120.6	32.9	1	2
465	900	1000	21637659	958.0	869.0	97.0	89.0	42.5	2	12
466	450	1000	21637654	923.3	830.0	95.0	93.3	44.5	6	12
467	600	990	21637661	920.0	795.7	120.0	124.3	46.0	6	3
468	1000	1000	21507654	886.4	778.2	111.8	108.2	44.1	1	2
469	500	900	21467658	870.0	790.0	106.7	80.0	36.9	7	3
470	1000	930	21377656	870.0	717.3	170.9	152.7	41.8	7	6
471	1650	940	21237662	875.6	734.4	163.9	141.1	40.7	2	6
472	600	930	21227668	850.0	697.1	194.3	152.9	38.2	1	3
473	1000	910	21157658	793.6	698.2	156.4	95.5	31.4	0	6
474	1000	1000	21657648	881.8	774.5	135.5	107.3	38.4	2	2
475	1400	1030	21787648	915.3	712.0	237.3	203.3	40.6	2	12
476	600	980	21837759	891.4	737.1	202.9	154.3	37.3	3	2
477	1500	790	22617637	687.5	563.8	215.0	123.8	29.9	2	3
MONADHLIATH REGION										
120	2000	1070	24307869	1012.9	821.4	228.1	191.4	40.0	2	1
124	350	1030	24357862	984.0	760.0	274.0	224.0	39.3	2	1
125	2750	1100	24347876	1046.2	753.4	311.4	292.8	43.2	1	1
126	650	1090	24467875	991.3	853.8	210.0	137.5	33.2	0	1
127	1900	1160	24137866	1036.0	856.5	240.5	179.5	36.7	2	1
128	600	990	24237855	961.4	842.9	147.1	118.6	38.7	2	1
129	750	1110	24227879	1065.6	958.9	130.0	106.7	39.4	0	1
130	500	1130	24197876	1105.0	1013.3	131.7	91.7	34.8	0	1
131	1150	1050	24327889	1036.2	806.9	288.5	229.2	38.5	3	1
132	750	1050	24407895	1000.0	881.1	148.9	118.9	38.6	2	1
133	700	1010	24197889	830.0	703.8	128.8	126.3	44.4	0	12

134	450	900	24117895	830.0	648.3	245.0	181.7	36.6	1	5
135	700	1020	24367896	906.3	776.3	142.5	130.0	42.4	0	1
136	1450	970	24847909	896.9	771.9	145.0	125.0	40.8	1	1
137	750	930	24977916	883.3	775.6	145.6	107.8	36.5	2	1
138	450	860	24317978	755.0	646.7	131.7	108.3	39.4	2	1
139	250	880	24077979	835.0	745.0	110.0	90.0	39.3	7	1
140	1000	820	24338016	689.1	570.9	144.5	118.2	39.3	0	1
141	500	810	24418021	700.0	556.7	193.3	143.3	36.6	7	1
142	1000	900	25057924	835.5	707.3	170.0	128.2	37.0	0	1
143	950	930	25647989	889.1	761.8	144.5	127.3	41.4	2	1
144	1350	760	25198092	706.0	539.3	227.3	166.7	36.2	1	3
145	750	830	26247974	783.3	663.3	146.7	120.0	39.3	1	1
146	1050	850	26288012	796.7	714.2	93.3	82.5	41.5	2	1
147	900	840	26247994	801.0	684.0	176.0	117.0	33.6	1	1
148	800	950	26368017	876.7	758.9	175.6	117.8	33.9	5	1
149	1650	950	26378019	895.6	742.2	209.4	153.3	36.2	1	1
150	650	930	26828044	886.3	805.0	110.0	81.3	36.5	3	1
153	400	820	23957897	720.0	646.0	116.0	74.0	32.5	1	5
154	600	1040	23877862	958.6	872.9	148.6	85.7	30.0	0	1
155	300	1050	23887852	922.5	737.5	217.5	185.0	40.4	1	1
156	1650	1050	23847847	1007.8	837.8	208.9	160.0	37.5	2	1
157	550	1050	23897849	865.7	757.1	141.4	108.6	37.5	3	1
158	900	1050	23887844	943.0	793.0	185.0	150.0	39.0	3	1
159	500	1050	23867846	1026.7	926.7	108.3	100.0	42.7	2	1
160	800	1050	23897850	908.9	767.8	174.4	141.1	39.0	2	1
449	1100	830	23427892	947.8	850.5	236.5	173.0	36.2	0	12
450	800	1040	23867862	991.5	747.1	161.4	118.6	36.3	0	12
454	600	800	22947897	782.9	675.7	142.9	107.1	36.9	2	12
455	400	710	23157918	640.0	528.0	176.0	112.0	32.5	1	12

SKYE AND RHUM

358	1250	890	14798185	726.4	518.6	232.9	207.9	41.8	1	10
359	1100	890	14668188	800.0	618.3	190.8	181.7	43.6	1	10
360	1600	890	14628194	829.4	479.4	422.4	343.5	39.1	5	10
361	2200	940	14568196	838.7	496.5	468.3	342.2	36.2	1	10
362	2700	990	14508209	835.0	648.9	255.7	186.1	36.0	4	10
363	500	880	14668192	796.7	620.0	200.0	176.7	41.5	0	10
364	1600	940	14468203	762.4	475.3	297.1	287.1	44.0	7	10
365	1400	990	14508210	876.7	607.3	298.0	269.3	42.1	6	10
366	2200	990	14438219	892.6	496.5	499.6	396.1	38.4	6	10

367	700	930	14368214	685.0	447.5	308.8	237.5	37.6	7	10
368	900	970	14318225	690.0	522.0	189.0	168.0	41.6	7	10
369	600	850	14348239	580.0	418.6	160.0	161.4	45.3	7	10
370	800	930	14418230	613.3	535.6	85.6	77.8	42.3	7	10
371	1750	970	14148228	871.6	634.2	261.1	237.4	42.3	7	10
372	900	920	14468234	874.0	691.0	224.0	183.0	39.2	6	10
373	3500	900	14458237	778.3	478.6	363.1	299.7	39.5	0	10
374	2200	960	14598242	790.0	521.3	313.5	268.7	40.6	7	10
375	2050	960	14648252	854.5	730.9	174.1	123.6	35.4	7	10
376	1200	940	14628204	734.6	510.0	200.0	224.6	48.3	1	10
377	1550	980	14558205	864.1	649.4	248.2	214.7	40.9	0	10
378	2500	980	14488214	818.8	559.6	313.8	259.2	39.6	1	10
379	3300	970	14458228	877.4	404.4	693.2	472.9	34.3	3	10
380	2000	970	14668253	851.4	612.9	301.9	238.6	38.3	1	10
381	1100	960	14658259	722.5	470.8	369.2	251.7	34.3	0	10
382	1500	960	14738258	515.0	311.9	249.4	203.1	39.2	1	10
383	1100	970	14738251	800.0	529.2	382.5	270.8	35.3	1	10
384	1000	960	14768246	682.7	430.9	358.2	251.8	35.1	1	10
385	1200	770	14778245	673.1	515.4	210.0	157.7	36.9	3	10
386	800	650	15158271	623.3	432.2	294.4	191.1	33.0	1	9
387	1200	730	15208288	585.4	393.1	280.0	192.3	34.5	1	9
388	700	730	15088252	688.8	490.0	206.3	198.8	43.9	2	9
389	1300	810	15298235	646.4	368.6	386.4	277.9	35.7	0	10
390	600	490	15268243	452.9	274.3	247.1	178.6	35.8	1	12
391	750	810	15328232	714.4	500.0	271.1	214.4	38.3	2	10
392	900	720	15388228	655.0	417.0	297.0	238.0	38.7	0	10
393	1850	930	15328218	746.0	424.5	441.0	321.5	36.1	7	10
394	1200	700	15448242	589.2	470.0	152.3	119.2	38.1	1	10
395	1100	710	15908230	607.5	393.3	297.5	214.2	35.7	3	9
396	800	580	15938221	536.7	360.0	246.7	176.7	35.6	2	9
397	500	710	15878238	540.0	460.0	98.3	80.0	39.1	2	12
398	950	710	15908233	567.3	417.3	218.2	150.0	34.5	1	9
399	900	930	16018235	553.0	428.0	156.0	125.0	38.7	0	9
400	800	730	16038232	607.8	381.1	274.4	226.7	39.6	1	9
401	500	770	15168298	623.3	355.5	355.0	268.3	37.1	3	10
402	600	700	15228291	492.9	330.0	217.1	162.9	36.9	0	9
403	450	770	15148300	731.7	610.0	188.3	121.7	32.9	0	10
488	1300	760	13777934	726.4	430.7	369.3	295.7	38.7	2	10

489	650	780	13797941	686.2	517.5	202.5	168.8	39.8	2	10
490	700	780	13757960	692.5	531.2	238.8	161.2	34.0	0	10
491	500	530	13567941	478.3	355.0	121.7	130.0	46.9	0	10
492	400	780	13768045	662.0	562.0	102.0	100.0	44.4	0	10
493	300	780	13787945	722.5	615.0	137.5	107.5	38.0	1	10
494	850	810	13937953	691.0	406.0	368.0	285.0	37.8	7	10
495	1250	810	13947944	512.1	383.6	190.0	128.6	34.1	2	10
496	400	810	14007952	566.0	412.0	182.0	154.0	40.2	2	10
497	550	810	13937949	733.3	580.0	221.7	153.3	34.7	3	10
498	400	900	14007955	502.0	398.0	144.0	104.0	35.8	1	10
499	1200	570	13297989	512.3	391.5	147.7	120.8	39.3	7	9
500	600	700	13757957	661.4	398.6	292.9	262.9	41.9	5	10

APPENDIX 2 : THE ORIENTATION OF ROCK WALLS

Key to Mid Point aspects

Code	Orientation ° east of north
0	0
1	45
2	90
3	135
4	180
5	225
6	270
7	315

No	Crest Length	Mid Point Aspect	Vector (°)	Magnitude	Strength (%)
1	1200	1	31.6	12.2	93.6
2	950	0	12.1	8.1	73.9
3	2850	0	358.3	19.9	66.4
4	2300	1	39.4	14.6	60.6
5	450	1	61.3	5.0	83.9
6	2400	1	41.5	23.3	93.1
7	2050	3	121.0	17.6	80.0
8	2000	0	29.0	19.0	90.4
9	1600	0	290.2	9.5	56.1
11	1350	4	168.4	10.6	70.5
12	900	4	214.2	7.5	75.5
13	2700	1	41.6	18.9	67.4
14	900	1	43.8	6.0	59.5
16	650	1	50.7	7.2	89.5
17	950	1	35.7	8.8	79.7
18	2300	2	69.8	18.9	78.9
19	550	0	6.0	6.7	96.3
20	2450	1	1.6	19.8	76.1
21	500	3	105.2	4.3	71.2
22	1100	5	229.7	8.6	71.4
26	600	3	97.9	4.8	69.2
27	950	2	49.5	9.0	81.6
28	700	1	38.9	7.7	96.7
30	950	2	62.0	9.7	87.9
31	3050	0	61.0	21.4	66.1
32	600	2	52.6	6.2	88.0
33	700	1	56.7	7.0	87.2
34	1500	4	177.6	7.0	43.5
35	1650	4	199.0	12.6	70.2
36	2400	3	207.3	16.4	65.7
37	3800	0	29.0	24.4	62.4
38	600	7	334.1	6.5	92.5
40	700	1	22.5	7.4	92.4
41	500	2	52.9	5.2	86.2
42	450	0	22.5	5.5	92.4
44	1000	1	37.0	8.0	73.0
45	2100	2	99.0	11.2	51.0
46	350	1	17.8	4.6	92.7
47	650	0	0.0	8.0	100.0
48	650	0	10.8	7.5	94.3
49	400	2	76.0	4.1	82.5
50	1800	2	103.8	14.8	77.9
51	600	7	321.0	6.7	97.3
52	2100	4	139.7	17.1	77.2
53	1800	2	89.0	16.5	87.0
55	500	2	61.3	5.0	83.9
56	1000	2	84.3	10.0	91.4
57	650	0	6.2	6.6	82.2
58	500	2	61.3	5.0	83.9
59	800	0	19.9	8.3	92.5
60	700	2	100.4	6.2	77.8
61	1100	3	102.8	8.3	69.0

62	2500	1	41.2	21.4	82.2
63	1100	4	202.5	9.2	77.0
64	800	1	23.7	7.8	86.4
116	1200	6	278.3	11.8	91.0
117	300	6	260.3	2.4	61.2
119	550	7	334.1	6.5	92.5
65	1200	1	11.6	10.6	81.4
66	1650	0	357.3	14.8	82.2
67	400	4	180.0	3.0	60.0
68	400	0	0.0	5.0	100.0
69	650	7	337.5	7.4	92.4
314	900	1	62.1	8.2	81.9
315	900	3	99.2	7.9	70.4
316	600	0	347.6	6.6	93.8
317	1000	7	313.0	8.5	77.6
318	2750	0	20.5	17.8	61.3
320	1700	2	115.4	12.6	70.2
321	850	6	260.8	7.0	70.4
322	800	2	82.9	8.1	89.6
323	950	7	321.5	8.9	80.8
324	800	2	70.5	7.2	80.5
325	1500	2	83.8	7.7	48.1
326	350	2	65.3	4.1	81.6
327	550	2	80.5	6.1	71.9
328	700	6	262.9	5.8	71.9
329	1800	0	17.1	12.2	64.2
330	1000	0	348.7	8.7	79.1
331	1050	0	360.0	9.7	80.5
332	350	1	27.2	4.6	92.7
333	1050	1	26.4	11.1	92.6
334	900	2	76.2	7.2	71.6
335	850	2	71.6	7.6	76.3
336	1750	2	71.5	16.5	86.9
337	2050	2	86.9	18.7	84.9
338	1400	3	115.0	8.8	58.5
339	550	2	66.0	5.9	84.7
340	2000	2	110.9	17.0	81.0
341	1550	2	97.1	10.4	61.4
342	1100	2	66.1	9.5	78.9
343	1000	2	79.5	7.1	64.3
344	1150	2	45.0	11.2	86.5
345	850	4	180.0	8.0	80.0
346	950	6	29.3	6.9	63.0
347	900	7	292.5	6.0	59.9
348	3700	0	2.4	20.6	54.3
350	700	6	295.4	6.3	79.0
351	1000	7	327.1	8.1	73.9
352	600	2	80.3	4.2	59.7
353	2450	2	122.1	14.3	54.8
355	2100	1	55.7	10.1	46.0
357	1000	2	78.8	8.7	79.1
161	300	0	0.0	4.0	100.0
162	550	7	327.4	6.6	93.8
163	450	1	22.5	5.5	92.4
164	400	7	350.3	4.2	83.6
165	2250	0	359.7	20.2	83.1

166	1150	0	349.6	11.7	90.2
167	1900	1	70.8	14.7	73.6
168	700	2	94.1	5.8	73.0
169	1250	0	356.4	11.4	81.3
170	500	1	52.9	5.2	86.2
171	800	1	43.7	5.5	61.5
172	350	1	45.0	3.8	76.6
173	400	0	0.0	5.0	100.0
174	850	1	40.8	9.7	97.3
175	400	0	0.0	5.0	100.0
176	1000	7	301.7	9.2	83.6
178	700	0	348.3	7.0	87.2
180	1350	1	16.7	12.3	82.0
181	2150	7	333.4	15.9	69.0
182	550	0	340.9	6.5	92.5
183	800	2	55.2	8.0	88.4
184	1750	0	347.4	14.3	75.2
185	550	1	25.9	6.5	92.5
186	750	2	76.5	7.3	81.4
187	1000	5	199.9	8.3	75.7
188	600	0	12.4	6.6	93.8
189	600	1	39.0	6.7	96.3
190	550	7	334.1	6.5	92.5
191	350	0	350.3	4.2	83.6
192	250	1	22.5	3.7	92.4
193	250	2	57.8	3.2	80.0
194	350	1	36.5	4.8	95.2
196	350	0	342.2	4.6	92.7
198	600	1	6.0	6.7	96.3
199	800	1	360.0	8.4	93.5
200	300	5	242.1	2.4	60.0
201	400	7	342.2	4.6	92.7
202	500	0	345.4	5.6	93.3
203	1100	7	311.4	11.1	92.9
204	550	0	347.6	6.6	93.8
205	400	1	45.0	4.4	88.3
206	400	1	45.0	4.4	88.3
207	950	4	158.7	7.8	70.0
208	700	3	149.6	5.6	69.9
209	600	7	308.4	6.2	88.0
210	1550	1	360.0	16.4	96.9
211	1250	0	356.8	12.6	89.7
212	700	1	50.7	7.2	89.5
213	550	0	6.0	6.7	96.3
214	650	0	10.8	7.5	94.3
215	850	1	54.1	8.9	89.4
216	1050	1	18.6	11.1	92.6
217	600	0	347.6	6.6	93.8
218	500	0	14.6	5.6	93.3
219	1750	1	42.5	12.2	64.2
220	600	1	51.6	6.2	83.0
221	900	0	13.1	9.4	93.6
222	600	0	0.0	7.0	100.0
223	1200	7	17.4	10.4	80.2
224	300	0	0.0	10.4	100.0
225	800	0	14.6	8.4	93.3

226	800	6	293.7	7.8	86.4
227	1000	4	180.0	9.0	81.8
228	300	0	349.2	38	94.3
229	250	0	0.0	4.0	100.0
230	1050	0	346.4	8.5	70.7
231	1000	3	132.4	6.5	59.5
232	500	0	337.5	5.5	92.4
233	1100	1	40.7	9.4	78.3
234	300	2	71.6	3.2	79.1
235	800	0	344.3	7.8	87.0
236	1050	2	79.2	9.1	75.9
237	600	1	39.0	6.7	96.3
238	250	1	10.8	3.8	94.3
239	450	7	315.0	5.4	90.2
240	1050	1	36.1	9.2	76.5
241	800	1	340.1	8.3	92.5
243	800	0	9.5	8.5	94.8
244	800	1	66.3	7.8	86.4
245	600	0	360.0	6.4	91.6
246	2500	0	354.7	22.9	88.0
247	500	0	14.6	5.6	93.3
248	1300	0	6.0	13.5	96.3
250	250	0	315.0	3.4	85.4
251	300	0	0.0	4.0	100.0
252	600	0	347.6	6.6	93.8
253	1250	1	21.5	12.4	88.5
254	900	7	342.2	9.3	92.7
255	1350	2	73.7	10.7	71.2
256	1300	7	325.1	12.1	86.7
257	1750	0	335.1	16.5	86.8
258	1000	0	343.0	9.7	87.9
259	500	0	345.4	5.6	93.3
260	500	7	315.0	5.4	90.2
261	1050	1	21.3	10.5	87.9
262	1350	0	354.1	9.7	64.7
263	900	1	40.8	9.7	97.3
264	1050	7	339.3	10.0	83.4
265	800	0	11.9	6.3	69.5
266	650	1	20.6	6.9	85.7
267	350	1	17.8	4.6	92.7
268	1000	0	355.5	9.0	81.6
269	1350	1	61.6	9.0	60.2
270	1250	0	350.3	20.8	77.2
271	450	1	37.9	5.8	95.8
272	1700	0	9.1	12.6	70.2
273	550	7	315.0	5.8	83.3
274	850	7	346.9	9.4	93.6
275	500	5	206.6	3.2	52.7
276	1100	0	341.4	11.1	92.6
277	1150	0	356.5	10.6	81.4
278	1200	1	56.6	10.6	81.4
279	900	1	8.5	9.5	95.2
280	1350	2	82.4	10.8	71.7
281	1200	0	0.0	13.0	100.0
282	400	1	54.7	4.2	83.6
283	400	7	305.3	4.2	83.6

284	600	0	340.9	6.5	92.5
285	1150	4	147.5	9.8	75.1
286	600	0	25.9	6.5	92.5
288	900	0	17.8	9.3	92.7
289	700	1	50.7	7.2	89.5
290	600	1	45.0	6.4	91.6
291	550	0	6.0	6.7	96.3
292	700	1	39.8	7.7	96.7
293	1150	0	356.8	12.7	97.9
294	750	7	309.6	7.6	84.1
295	750	7	321.0	6.7	96.3
296	1100	0	18.6	11.1	92.6
297	1300	0	348.3	9.9	70.4
298	900	0	351.4	9.5	95.2
299	1000	1	33.2	10.3	94.0
300	600	0	347.6	6.6	93.8
301	1100	1	45.0	10.8	90.2
302	900	1	39.9	8.0	79.8
303	750	0	360.0	7.2	80.5
304	1100	1	63.1	10.0	83.6
305	700	0	10.8	7.5	94.3
306	1000	0	356.0	10.1	92.2
307	1250	1	3.8	10.8	77.2
308	1300	0	21.5	12.4	88.5
309	400	3	135.0	3.0	60.0
310	850	2	97.9	8.2	82.0
311	1250	1	0.7	9.4	66.9
312	900	2	112.5	5.2	52.3
313	700	1	50.7	7.2	89.5
478	700	6	270.0	8.0	100.0
479	500	1	45.0	6.0	100.0
484	1500	1	89.0	10.4	64.8
485	1000	2	94.5	9.0	81.6
486	2000	2	84.9	14.6	69.5
487	2200	7	353.1	20.0	87.1
511	1300	0	22.5	9.7	69.2
512	500	7	322.1	5.7	95.9
513	700	0	16.6	7.4	92.9
514	900	0	5.1	8.0	80.0
515	1500	1	68.1	9.5	59.4
516	800	2	96.1	7.6	84.4
517	2500	0	6.6	14.3	55.0
518	1100	2	94.4	6.6	55.2
519	2500	1	26.1	24.1	92.6
74	650	1	50.7	7.2	89.5
78	900	5	235.0	8.1	81.2
79	900	1	9.7	8.4	83.6
81	1550	7	315.0	16.4	96.6
83	650	2	75.7	6.9	86.5
84	300	1	34.2	3.8	94.3
85	900	7	319.2	9.7	97.3
86	3500	2	79.3	24.0	66.7
87	1100	1	57.0	10.2	84.8
88	2700	7	337.5	25.9	92.4
89	750	0	345.4	8.4	93.3
90	1800	0	348.1	15.1	79.5

91	1250	1	43.0	11.8	84.5
92	400	1	45.0	4.4	88.3
93	2000	1	16.3	15.7	74.8
94	950	3	130.6	9.3	84.7
95	300	1	34.2	3.8	94.3
96	600	2	58.6	6.0	85.7
97	550	0	360.0	5.8	83.3
98	650	0	337.5	7.4	92.4
99	1300	1	27.7	11.9	85.0
100	1600	0	2.7	11.4	66.9
101	600	2	63.4	5.4	77.1
102	700	1	50.7	7.2	89.5
103	500	0	14.6	5.6	93.3
104	1450	3	103.5	10.4	64.7
106	800	3	123.6	7.1	79.3
107	1100	0	21.3	10.5	87.9
109	900	2	88.1	8.7	87.9
111	1300	1	42.0	13.7	98.0
112	950	2	80.0	9.9	89.6
113	650	2	81.9	7.1	83.4
114	1350	0	1.5	11.4	75.8
115	250	3	117.5	2.4	60.0
121	900	0	4.2	9.7	97.3
414	1400	5	261.6	10.5	69.8
415	800	0	14.6	8.4	93.3
416	2700	0	33.9	22.0	78.5
417	1200	1	30.1	9.4	72.2
418	850	4	180.0	8.0	80.0
419	1000	3	124.0	7.4	67.1
420	1650	1	58.0	15.8	87.6
421	1300	1	51.6	12.3	88.0
422	1100	1	33.0	10.2	84.8
423	1800	1	41.2	12.3	65.0
424	1100	2	45.0	9.7	80.5
425	2900	2	55.4	25.0	83.4
426	1300	1	53.9	11.1	79.2
427	800	2	93.2	7.4	82.5
428	900	2	103.1	8.0	80.4
429	700	3	165.4	4.0	49.5
430	900	0	2.4	7.0	69.6
431	1000	7	323.2	9.9	90.3
432	1600	2	66.9	15.2	89.2
433	650	2	63.0	6.9	85.9
434	300	2	83.9	2.7	68.1
435	400	4	165.4	2.8	56.0
436	600	0	6.6	6.2	88.0
437	800	4	135.0	5.8	64.8
438	700	1	360.0	6.8	85.4
439	1500	2	97.4	10.0	62.7
440	1600	0	7.6	12.9	75.8
441	800	3	117.4	7.0	78.2
442	400	1	45.0	4.4	88.3
443	800	2	77.5	7.9	87.7
444	1200	0	353.7	8.0	61.5
445	1350	2	88.6	12.0	79.7
446	1000	3	87.9	8.0	72.3

447	1500	2	121.9	8.6	53.7
448	700	1	39.8	7.7	96.7
453	1400	1	68.2	12.2	81.6
456	1600	0	360.0	8.8	63.0
457	1300	1	72.0	9.7	53.9
458	1250	2	63.4	7.6	54.5
459	300	0	360.0	4.0	100.0
460	700	6	8.6	3.6	44.7
461	600	2	102.4	6.4	91.4
462	300	2	90.0	4.0	91.4
463	800	2	99.5	8.5	9.5
464	1500	1	34.3	10.1	6.3
465	900	2	76.0	8.8	88.0
466	450	6	298.7	5.0	83.8
467	600	6	289.1	6.5	92.5
468	1000	1	28.3	7.0	63.2
469	500	7	315.0	4.8	80.5
470	1000	7	328.1	9.4	85.4
471	1650	2	78.5	8.0	44.4
472	600	1	31.4	6.0	85.7
473	1000	0	13.3	9.2	86.9
474	1000	2	85.8	9.6	86.9
475	1400	2	49.9	11.7	78.0
476	600	3	14.2	5.6	79.7
477	1500	2	87.4	15.7	98.3
120	2000	2	113.5	9.3	44.3
124	350	2	76.0	4.1	82.5
125	2750	1	18.5	24.1	83.3
126	650	0	321.8	16.8	83.9
127	1900	2	120.4	16.8	83.9
128	600	2	94.4	6.4	77.6
129	750	0	355.4	8.7	97.1
130	500	0	340.1	5.0	83.5
131	1150	3	151.1	10.2	78.7
132	750	2	75.4	6.8	75.1
133	700	0	349.2	7.5	94.3
134	450	1	37.9	5.8	95.8
135	700	0	353.8	6.6	82.2
136	1450	1	104.4	9.2	57.7
137	750	2	68.9	6.7	74.4
138	450	2	52.9	5.2	86.2
139	250	7	325.8	3.8	94.3
140	1000	0	343.9	1.2	93.0
141	500	7	329.6	5.6	93.3
142	1000	0	7.7	10.5	95.5
143	950	2	97.5	8.6	87.3
144	1350	1	74.6	11.8	78.6
145	750	1	34.8	8.0	88.4
146	1050	2	117.2	9.3	77.3
147	900	1	54.1	8.9	89.4
148	800	5	230.4	7.3	81.4
149	1650	1	71.0	16.1	89.6
150	650	3	142.9	5.2	64.6
153	400	1	36.5	4.8	95.2
154	600	0	6.0	6.7	96.3
155	300	1	22.5	3.7	92.4

156	1650	2	98.8	10.1	55.9
157	550	3	119.2	5.2	74.2
158	900	3	67.5	8.2	81.6
159	500	2	70.1	5.0	83.5
160	800	2	80.9	6.3	70.2
449	1100	0	2.6	9.3	77.1
450	800	0	360.0	7.8	87.0
454	600	2	90.0	3.8	54.7
455	400	1	31.4	6.0	85.7
358	1250	1	45.0	12.2	87.4
359	1100	1	33.1	8.8	73.7
360	1600	5	208.7	10.7	62.8
361	2200	1	56.4	16.7	72.6
362	2700	4	171.1	15.2	54.3
363	500	0	7.1	5.8	95.8
364	1600	7	289.5	13.6	79.8
365	1400	6	276.8	9.4	62.9
366	2200	6	262.2	16.5	71.6
367	700	7	303.3	7.0	87.2
368	900	7	337.5	9.2	92.4
369	600	7	321.0	6.7	96.4
370	800	7	309.2	7.0	77.6
371	1750	7	299.5	13.9	73.0
372	900	6	301.2	7.2	71.6
373	3500	0	341.6	22.9	63.6
374	2200	7	319.1	12.2	53.1
375	2050	7	336.2	13.8	62.9
376	1200	1	20.3	9.9	75.8
377	1550	0	359.4	11.8	69.3
378	2500	1	37.6	22.1	84.9
379	3300	3	107.7	27.0	79.3
380	2000	1	17,9	11,6	55.4
381	1100	0	10.9	11.3	94.3
382	1500	1	36.0	13.5	84.6
383	1100	1	40.7	9.4	78.3
384	1000	1	53.7	9.4	85.0
385	1200	3	120.7	8.1	62.2
386	800	1	55.2	8.0	88.4
387	1200	1	64.2	10.4	80.0
388	700	2	51.2	6.6	82.2
389	1300	0	15,9	11.4	81.3
390	600	1	51.6	6.2	88.0
391	750	2	93.2	7.4	82.5
392	900	0	0.0	10.0	100.0
393	1850	7	312.6	16.8	84.0
394	1200	1	34.0	11.2	85.8
395	1100	3	116.1	8.7	72.6
396	800	2	60.7	7.8	87.0
397	500	2	61.3	5.0	83.9
398	950	1	35.7	8.8	79.7
399	900	0	13.1	9.4	93.6
400	800	1	45.0	8.4	93.5
401	500	3	125.6	4.4	72.5
402	600	0	6.0	6.3	96.3
403	450	0	14.6	5.6	93.3

488	1300	2	78.3	9.9	70.4
489	650	2	67.5	6.3	78.9
490	700	0	337.5	7.4	92.4
491	500	0	345.4	5.6	93.3
492	400	0	342.2	4.6	77.7
493	300	1	67.5	3.7	92.4
494	850	7	297.2	9.3	92.7
495	1250	2	79.0	10.2	93.3
496	400	2	125.0	4.0	100.0
497	550	3	120.4	5.6	93.3
498	400	1	45.0	4.0	100.0
499	1200	7	348.3	10.6	81.4
500	600	5	205.9	6.5	81.0

APPENDIX 3 : PROGRAM TO CALCULATE INSOLATION INCIDENT AT ROCK WALLS

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 FILE 'CORILITE'
       DIMENSION AZ(72),SUNALT(72),HILL(72),HILALT(72),SUNFL(72),
      1 SKYFL(72),HAS(72),MINS(72),GRMN(72),GRFL(72) ,FRAC(12),ADAY(12)
       REAL LIM1,LIM2,LAT
        INTEGER P,R1,R2
 C*** EQN FOR ABSORPTION OF RADIATION IN ATMOSPHERE (HARDIE)
       TRANS(X)=(ABSOR)**(1.0/SIN(X)-0.0018167*(1.0/SIN(X)-1.0)-
      1 0.002875*(1.0/SIN(X)-1.0)**2-.0008083*(1.0/SIN(X)-1.0)**3)
       PI=4.0*ATAN(1.0)
       FLUX=1.98
       SCATT=0.2
 C*** ATMOSPHERIC TRANSMISSIVITY FOR EACH DAY CALCULATED
       FRAC(1)=.8
       FRAC(2)=.8
       FRAC(3)=.79
       FRAC(4)=.78
       FRAC(5)=.775
       FRAC(6)=.77
       FRAC(7)=.76
       FRAC(8)=.77
       FRAC(9)=.785
       FRAC(10)=.795
       FRAC(11)=.805
       FRAC(12)=.81
 C*** DAYS INCLUDED IN CALCULATION
 C*** COUNTING FROM MARCH 21
       ADAY(1)=300.0
       ADAY(2)=331.0
       ADAY(3)=359.0
       ADAY(4)=25.0
       ADAY(5)=55.0
       ADAY(6)=86.0
       ADAY(7)=116.0
       ADAY(8)=147.0
       ADAY(9)=177.0
       ADAY(10)=208.0
       ADAY(11)=238.0
       ADAY(12)=269.0
 C*** READ IN CONSTANTS FOR MODEL ON THIS RUN AND
 C*** LOCATION DATA
       READ(5,100) R1,R2,GRAD,AC,LAT,THETA,GRADICE
 100   FORMAT(2I4,5F5.1)
       WRITE (6,101) R1,R2,GRAD,GRADICE,AC,LAT,THETA
 101   FORMAT('BASE WALL RADIUS =',I5/'CREST RADIUS =',I5/
      1'WALL GRADIENT =',F5.1/'ICE GRADIENT =',F5.1/
      2'ROCK WALL MID POINT ASPECT =',F6.1/'LATITUDE =',F5.1/
      3'ASPECT POINT P WRT ROCKWALL ASPECT =' F6.1//)
       WRITE(6,502) SCATT,FLUX
       THETA=THETA*PI/180.0
       GRAD=GRAD*PI/180.0
       GRADICE=GRADICE*PI/180.0
       AC=AC*PI/180.0
       DO 37 MM=1,17
       R=20*MM
       TOTGRCL=0.0
       AMAX=0.0
 C*** FIRST CALCULATE LOCATION OF POINT RELATIVE TO
 C*** ROCK WALL MIDPOINT
 C*** HEIGHT OF P
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      ZP=(R-R1)*TAN(GRAD)
      CD=ABS(R*COS(THETA-PI/2))
C*** CALCULATE INTERNAL ANGLE DEPENDENT ON RELATIVE POSITION
C*** OF P TO ROCK WALL MIDPOINT ANGLE
      IF((THETA-PI/2).GT.(PI/2)) GO TO 38
      IF (ABS(THETA-PI/2).LT.0.000001) GO TO 141
      TANPQ1=(R1+(R*COS(THETA-PI/2)))/(R*SIN(THETA-PI/2))
      TANPQ2=(R2+R*COS(THETA-PI/2))/(R*SIN(THETA-PI/2))
      TANPQ3=(R1-R*COS(THETA-PI/2))/(R*COS(THETA-PI/2)*TAN(THETA-PI/2
      TANPQ4=(R2-R*COS(THETA-PI/2))/(R*COS(THETA-PI/2)*TAN(THETA-PI/2
      GO TO 39
141   ACPQ1=2*PI+(AC-PI/2)
      ACPQ2=2*PI+AC-PI/2
      ACPQ3=PI/2+AC
      ACPQ4=PI+AC
      GO TO 26
38    IF (ABS(THETA-(3*PI/2)).LT.0.000001) GO TO 142
       TANPQ1=(R1+R*COS(3*PI/2-THETA))/(R*SIN(3*PI/2-THETA))
      TANPQ2=(R2+R*COS(3*PI/2-THETA))/(R*SIN(3*PI/2-THETA))
      TANPQ3=(R1-R*COS(3*PI/2-THETA))/(R*SIN(3*PI/2-THETA))
      TANPQ4=(R2-R*COS(3*PI/2-THETA))/(R*SIN(3*PI/2-THETA))
      GO TO 39
142   ACPQ1=PI/2+AC
      ACPQ2=PI/2+AC
      ACPQ3=2*PI+AC-PI/2
      ACPQ4=2*PI+AC-PI/2
      GO TO 26
39     PQ1=ATAN(TANPQ1)
      PQ2=ATAN(TANPQ2)
      PQ3=ATAN(TANPQ3)
      PQ4=ATAN(TANPQ4)
      IF((CD.LT.R1).OR.(CD.GT.R2)) GO TO 24
      IF(THETA.GT.PI) GO TO 25
      ACPQ1=AC-PQ1
      ACPQ2=AC-PQ2
      ACPQ3=AC-PQ3
      ACPQ4=AC+PQ4
      GO TO 26
25    ACPQ1=AC+PQ1
      ACPQ2=AC+PQ2
      ACPQ3=AC+PQ3
      ACPQ4=AC-PQ4
      GO TO 26
24    IF(THETA.GT.PI) GO TO 27
      ACPQ1=AC-PQ1
      ACPQ2=AC-PQ2
      ACPQ3=AC+PQ3
      ACPQ4=AC+PQ4
      GO TO 26
27    ACPQ1=AC+PQ1
      ACPQ2=AC+PQ2
      ACPQ3=AC-PQ3
      ACPQ4=AC-PQ4
26    IF(ACPQ1 .LE. 0.0) ACPQ1=ACPQ1+2*PI
      IF(ACPQ1 .GT. 2*PI) ACPQ1=ACPQ1-2*PI
      IF(ACPQ2 .LE. 0.0) ACPQ2=ACPQ2+2*PI
      IF(ACPQ2 .GT. 2*PI) ACPQ2=ACPQ2-2*PI
      IF(ACPQ3 .LE. 0.0) ACPQ3=ACPQ3+2*PI
      IF(ACPQ3 .GT. 2*PI) ACPQ3=ACPQ3-2*PI
      IF(ACPQ4 .LE. 0.0) ACPQ4=ACPQ4+2*PI
```

```
      IF(ACPQ4 .GT. 2*PI) ACPQ4=ACPQ4-2*PI
      IF (ACPQ1 .LT. ACPQ2) GO TO 20
      X=ACPQ1
      ACPQ1=ACPQ2
      ACPQ2=X
20    IF (ACPQ3 .LT.ACPQ4) GO TO 21
      X=ACPQ3
      ACPQ3=ACPQ4
      ACPQ4=X
21    WRITE(6,128) ACPQ1,ACPQ2,ACPQ3,ACPQ4
128   FORMAT(4(F12.8,4X))
C*** GO ROUND 360 DEG WITH 20 MIN (5DEG) SAMPLING INTERVAL
            DO 10 J=1,72
      ANGLE=J*5.0*PI/180.0
      IF(THETA.GT. PI) GO TO 4
      SIGMA=THETA-PI/2
      GO TO 2
4     SIGMA=3*PI/2-THETA
2     CD=R*COS(SIGMA)
      DQ=R*SIN(SIGMA)*TAN(ABS(AC-ANGLE))
      DQ=ABS(DQ)
      CD=ABS(CD)
      ZZZ=0.0
      IF((ABS(ACPQ1-ACPQ2).LT.0.000001).AND.(ABS(ACPQ3-ACPQ4)
     1 .LT.0.000001)) ZZZ=1.0
      IF (ZZZ.EQ.0.0) GO TO 558
      IF ((ABS(ACPQ1-ACPQ3).GE.3.1410).AND.(ABS(ACPQ1-ACPQ3).
     1 LE. 3.1420)) ZZZ=2.0
      IF (ZZZ.EQ.1.0) GO TO 558
      IF (ZZZ.EQ.2.0) GO TO 60
558   IF((ACPQ1.LT.ACPQ2).AND.(ACPQ2.LT.ACPQ3).AND.(ACPQ3.LT.ACPQ4
     1).AND.((ACPQ4-ACPQ1).LT.PI)) GO TO 50
      IF((ACPQ1.LT.ACPQ2).AND.(ACPQ2.GT.ACPQ3).AND.(ACPQ3.LT.ACPQ4)
     1.AND.(ABS(ACPQ4-ACPQ1).LT.PI))GO TO 51
      IF((ABS(ACPQ2-ACPQ3).GT.3.14).AND.(ACPQ2.LT.ACPQ3).AND.(
     1ABS(ACPQ4-ACPQ1).GT.3.14)) GO TO 52
      IF((ABS(ACPQ2-ACPQ3).GT.3.14).AND.(ACPQ2.GT.ACPQ3).AND.
     1 (ABS(ACPQ1-ACPQ4) .GT. 3.14)) GO TO 57
      IF((ABS(ACPQ1-ACPQ2).GT.PI).AND.(ABS(ACPQ4-ACPQ1).GT.PI)) GO TO
     153
      IF((ABS(ACPQ1-ACPQ2).GT.PI).AND.(ABS(ACPQ1-ACPQ4).LT.PI))
     1GO TO 54
      IF((ABS(ACPQ3-ACPQ4).GT.PI).AND.(ABS(ACPQ3-ACPQ2).LT.PI))
     1GO TO 55
      IF((ABS(ACPQ3-ACPQ4).GT.PI).AND.(ABS(ACPQ3-ACPQ2).GT.PI))
     1GO TO 56
60    CQ=P2
      IF (AC.EQ.2*PI) GO TO 61
C*** CALCULATE ANGLE LIMIT INSIDE WHICH THE SUN MAY BE
C*** INCIDENT AT POINT P
      LIM1=ACPQ3
      LIM2=ACPQ1
      GO TO 15
61    LIM1=ACPQ1
      LIM2=ACPQ3
      GO TO 16
50    LIM1=ACPQ2
      LIM2=ACPQ3
      IF((ANGLE.GT.ACPQ1).AND.(ANGLE.LT.ACPQ2)) GO TO 6
      IF((ANGLE.GE.ACPQ3).AND.(ANGLE.LE.AC)) GO TO 7
```

```
      IF((ANGLE.GT.AC).AND.(ANGLE.LE.ACPQ4)) GO TO 6
      CQ=R2
      GO TO 15
6     CQ=CD+DQ
      GO TO 15
7     CQ=CD-DQ
      GO TO 15
8     CQ=DQ-CD
      GO TO 15
51    LIM1=ACPQ4
      LIM2=ACPQ1
      IF((ANGLE.GT.ACPQ3).AND.(ANGLE.LE.AC)) GO TO 6
      IF((ANGLE.GT.AC).AND.(ANGLE.LE.ACPQ4)) GO TO 7
      IF((ANGLE.GE.ACPQ1).AND.(ANGLE.LE.ACPQ2)) GO TO 8
      CQ=R2
      GO TO 15
53    LIM1=ACPQ4
      LIM2=ACPQ1
      IF((ANGLE.GE.ACPQ3).AND.(ANGLE.LE.AC)) GO TO 6
      IF((ANGLE.GT.AC).AND.(ANGLE.LE.ACPQ4)) GO TO 7
      IF((ANGLE.GE.ACPQ4)) GO TO 8
      IF(ANGLE.LE.ACPQ1) GO TO 8
      CQ=R2
      GO TO 15
54    LIM1=ACPQ1
      LIM2=ACPQ3
      IF((ANGLE.GE.ACPQ2).OR.(ANGLE.LE.ACPQ1)) GO TO 7
      IF((ANGLE.GE.ACPQ3).AND.(ANGLE.LE.AC)) GO TO 7
      IF((ANGLE.GT.AC).AND.(ANGLE.LT.ACPQ4)) GO TO 6
      CQ=R2
      GO TO 15
55    LIM1=ACPQ3
      LIM2=ACPQ1
      IF((ANGLE.GE.ACPQ4).AND.(ANGLE.LE.AC)) GO TO 6
      IF(ANGLE.GT.AC) GO TO 7
      IF(ANGLE.LE.ACPQ3) GO TO 7
      IF((ANGLE.GE.ACPQ1).AND.(ANGLE.LE.ACPQ2)) GO TO 8
      CQ=R2
      GO TO 15
56    LIM1=ACPQ2
      LIM2=ACPQ4
      IF((ANGLE.GE.ACPQ1).AND.(ANGLE.LE.ACPQ2)) GO TO 8
      IF((ANGLE.GE.ACPQ4).AND.(ANGLE.LE.AC)) GO TO 7
      IF((ANGLE.GT.AC).OR.(ANGLE.LE.ACPQ3)) GO TO 6
      CQ=R2
      GO TO 15
52    LIM1=ACPQ4
      LIM2=ACPQ1
      IF((ANGLE.GE.ACPQ3).AND.(ANGLE.LE.AC))GO TO 32
      IF((ANGLE.GT.AC).AND.(ANGLE.LE.ACPQ4)) GO TO 33
      IF((ANGLE.GE.ACPQ1).AND.(ANGLE.LE.ACPQ2))GO TO 34
      CQ=R2
      GO TO 16
32    CQ=CD+DQ
      GO TO 16
33    CQ=CD-DQ
      GO TO 16
34    CQ=DQ-CD
      GO TO 16
57    LIM1=ACPQ2
      LIM2=ACPQ3
      IF((ANGLE.GE.ACPQ1).AND.(ANGLE.LE.ACPQ2)) GO TO 34
```

```
      IF((ANGLE.GE.ACPQ3).AND.(ANGLE.LE.ACPQ4).AND.
     1(AC.GE.(2*PI-.001)))
     1 GO TO 32
      IF((AC.LT.ACPQ3).AND.((ANGLE.GT.ACPQ3).AND.(ANGLE.LT.ACPQ4)))
     1 GO TO 32
      IF((ACPQ3.LT.AC).AND.((ANGLE.GT.ACPQ3).AND.(ANGLE.LT.AC))
     1.AND.(AC.LE.PI)) GO TO  33
      IF((ANGLE.GT.AC).AND.(ANGLE.LT.ACPQ4)) GO TO 32
      CQ=R2
      GO TO 16
15    IF ((LIM1.GE.6.282).AND.(LIM1.LE.6.284)) LIM1=0.0
      IF(ANGLE.GT.(5.0*PI/180.0)) GO TO 14
      DEG1=LIM1*180/PI
      DEG2=LIM2*180/PI
      WRITE(6,112)DEG1,DEG2,CQ
112   FORMAT('NO HILL BETWEEN',6X,2F7.2,F6.2)
14    IF((ANGLE.GT.LIM1).AND.(ANGLE.LT.LIM2)) GO TO 86
      GO TO 18
16    IF ((LIM1.GE.6.282).AND.(LIM1.LE.6.284)) LIM1=0.0
      IF (ANGLE.GT.(5.0*PI/180.0)) GO TO 9

      DEG1=LIM1*180/PI
      DEG2=LIM2*180/PI
      WRITE(6,113) DEG1,DEG2,CQ
113   FORMAT('NO HILL FROM',6X,F7.2,6X,'TO',6X,F7.2,F6.2)
9     IF((ANGLE.GT.LIM1).OR.(ANGLE.LT.LIM2)) GO TO 86
18      OHM=PI+THETA+AC-ANGLE
      CQ=ABS(CQ)
      IF (GRADICE.EQ.0.0) GO TO 123
      HTICE=((R2-R1)/COS(GRAD))*2.0/3.0
       ALTICE=HTICE*SIN(GRAD)
      IF (GRADICE.EQ.0.0) GO TO 123
      RICE=ALTICE/TAN(GRADICE)
      IF(R.LT.R1) GO TO 63
      IF((R.GE.R1).AND.(R.LT.RICE)) GO TO 64
C     R LARGER THAN RICE
123   IF (GRADICE.EQ.0.0) RICE=0.0
      IF (R.GE.R1) ZP=(R-R1)*TAN(GRAD)
      IF (R.LT.R1) ZP=0.0
      IF (CQ.LT.R2) GO TO 62
65    ZS=(R2-R1)*TAN(GRAD)-ZP
      R22=R2*1.0
      COSPHI=COS(PI-(ARSIN((R/R22)*SIN(OHM)))-OHM)
      GO TO 66
62    IF (CQ.GE.R1) ZS=(CQ-R1)*TAN(GRAD)-ZP
      IF (CQ.LT.R1) ZS=0.0-ZP
68    COSPHI=COS(PI-(ARSIN((R/CQ)*SIN(OHM)))-OHM)
      GO TO 66
64    ZP=CD*TAN(SIGMA)*TAN(GRADICE)+(R-R1)*TAN(GRAD)
      IF (CQ.LT.R2) GO TO 62
      GO TO 65
63    ZP=CD*TAN(SIGMA)*TAN(GRADICE)
      IF (CQ.LT.R2) GO TO 62
      GO TO 65
66    IF (ZS.LE.0.0) GO TO 86
      IF (CQ.LT.R2) GO TO 155
      PS=SQRT(R2**2+R**2-2*R*R2*COSPHI)
      GO TO 166
155   PS=SQRT(CQ**2+R**2-2*R*CQ*COSPHI)
166   HILL(J)=ATAN(ZS/PS)
      HILLX=HILL(J)*180.0/PI
```

```
      GO TO 87
86    HILL(J)=0.0
      HILLX=0.0
87    A=ANGLE*180.0/PI
C*** WRITE OUT SUM FOR INDIVIDUAL SAMPLE POINTS (72)
      WRITE(6,111) A,CQ,ZS,PS,HILLX
111   FORMAT(F5.0,4F6.1)
10    CONTINUE
      DO 40 JKL=1,12
      IF((ABS(THETA-PI/2).LT.0.005).OR.(ABS(THETA-3*PI/2).LT.
     1 0.005)) RICE=0.0
11     IF (R.GE.RICE) GO TO 117
      IF (R.GE.R1) GRALT=(PI/2-GRAD)
      IF (R.LT.R1) GRALT=(PI/2-GRADICE)
      GRAZ=AC+THETA+PI
      GO TO 118
117   IF (R.GE.R1) GRALT=(PI/2-GRAD)
      IF (R.LT.R1) GRALT=(PI/2-GRADICE)
      GRAZ=AC+THETA+PI
118    ABSOR=FRAC(JKL)
      DAY=ADAY(JKL)
      DEC=ARSIN(1/2.5129*SIN(DAY/365.25*2.0*PI))
      LAT=LAT*PI/180.0
      HRIS=ARCOS(-TAN(LAT)*TAN(DEC))
C
      DO 987 I=1,72
      IF (I-36) 41,41,42
41    HAS(I)=PI*(1.0+FLOAT(5*I)/180.0)
      GO TO 3
42    HAS(I)=PI/180.0*FLOAT(5*(I-36))
3     AZ1=ATAN2(-SIN(HAS(I)),COS(LAT)*TAN(DEC)-SIN(LAT)*COS(HAS(I)))
       IF (AZ1) 44,44,45
44    AZ(I)=2.0*PI+AZ1
      GO TO 987
45    AZ(I)=AZ1
987    CONTINUE
      DO 120 I=1,72
      J=INT(72.0*AZ(I)/2.0/PI+0.5)
      HILALT(I)=HILL(J)
      SINA=SIN(LAT)*SIN(DEC)+COS(LAT)*COS(DEC)*COS(HAS(I))
      IF (SINA) 46,46,47
46    SUNALT(I)=0.0
      GO TO 120
47    SUNALT(I)=ARSIN(SINA)
120    CONTINUE
      SKAREA=0.0
C
      DO 102 I=1,72
      SKAREA=SKAREA+SIN(HILL(I))/72
102   CONTINUE
      K=INT((PI-HRIS)/5.0*180.0/PI-1.0)
      DO 103 I=1,K
      SUNFL(I)=0.0
      SKYFL(I)=0.0
      MINS(I)=0.0
      GRFL(I)=0.0
      GRMN(I)=0.0
103   CONTINUE
      L=72-K
      DO 104 I=L,72
      SUNFL(I)=0.0
      SKYFL(I)=0.0
```

```
      MINS(I)=0.0
      GRFL(I)=0.0
      GRMN(I)=0.0
104   CONTINUE
C
      M=K+1
      N=72-K-1
      DOC*** IF SUNALT LES THAN 2DEG ABOVE HORIZON DISCOUNT IT
 105  I=M,N
      IF (SUNALT(I)-0.04) 81,81,82
81    SKYFL(I)=0.0
      GO TO 83
82    SKYFL(I)=FLUX*TRANS(SUNALT(I))*SCATT*(1.0-SKAREA)*SIN(SUNALT(I))
83    IF (SUNALT(I)-HILALT(I)) 28,28,29
28    SUNFL(I)=0.0
      MINS(I)=0.0
      GRFL(I)=0.0
      GRMN(I)=0.0
      GO TO 105
29     IF (SUNALT(I)-0.04) 92,92,91
92    SUNFL(I)=0.0
      MINS(I)=0.0
      GRFL(I)=0.0
      GRMN(I)=0.0
      GO TO 105
91    SUNFL(I)=FLUX*TRANS(SUNALT(I))*SIN(SUNALT(I))
      MINS(I)=20.0
      DAZ=GRAZ-AZ(I)
      CC=SIN(GRALT)*SIN(SUNALT(I))+COS(GRALT)*COS(SUNALT(I))*COS(DAZ)
      IF(CC) 601,601,602
601   GRFL(I)=0.0
      GRMN(I)=0.0
      GO TO 105
602   GRFL(I)=FLUX*TRANS(SUNALT(I))*CC
      GRMN(I)=20.0
105   CONTINUE
C
      CALS1=0.0
      CALS2=0.0
      HOURS=0.0
      GRHRS=0.0
      GRCAL=0.0
C
      DO 106 I=1,72
      CALS1=CALS1+20.0*SUNFL(I)
      CALS2=CALS2+20.0*SKYFL(I)
      HOURS=HOURS+MINS(I)/60.0
      GRHRS=GRHRS+GRMN(I)/60.0
      GRCAL=GRCAL+20.0*GRFL(I)
106   CONTINUE
      LAT=LAT/PI*180.0
      DEC=DEC/PI*180.0
      GRALT=GRALT/PI*180.0
      GRAZ=GRAZ/PI*180.0
      HRIS=HRIS/PI*180.0
      DO 107 I=1,72
      HAS(I)=HAS(I)/PI*180.0
      SUNALT(I)=SUNALT(I)*180.0/PI
      AZ(I)=AZ(I)*180.0/PI
      HILALT(I)=HILALT(I)*180.0/PI
107   CONTINUE
```

```
      HRIS1=360.0-HRIS
      STHETA=THETA*180.0/PI
      WRITE(6,510) R,STHETA
510   FORMAT('POSITION OF POINT P'/'DISTANCE FROM ORIGIN =',
     1I5,15X,'ANGULAR PCSITION WRT ROCKWALL ASPECT',
     1F6.1//)
C
      WRITE(6,512) SKAREA
502   FORMAT(26HPROPORTION OF SCATTERING =,F5.2,/
     132HSOL CONTANST (CALS CM-2 MIN-1) =,F5.2,/)
512   FORMAT(47HPROPORTION OF HEMISPHERE OBSCURED BY BACKWALL =,F5.2)
      WRITE(6,700) GRAZ,GRALT
700   FORMAT(16HGROUND AZIMUTH =,F6.1,17HGROUND ALTITUDE =,F6.1)
      WRITE(6,508) HOURS,CALS1,CALS2,GRAD,GRHRS,GRCAL
508   FORMAT(1H1,42HTOTAL SUNLIT HOURS ON HORIZONTAL SURFACE =,F5.1//
     152H0TOTAL DIRECT SUNLIGHT ON HORIZONTAL SURFACE(CALS) =,F7.1
     2//33H0TOTAL SCATTERED SKYLIGHT(CALS) =,F7.1//
     345H0TOTAL GROUNDLIT HOURS ON SLOPING SURFACE OF,F7.2,2H0=,F5.1
     4//22H0TOTAL GROUND INCOME =,F7.1)
      MONTH=31
      IF ((JKL.EQ.4) .OR.(JKL.EQ.6).OR.(JKL.EQ.9).OR.(JKL.EQ.11))
     1 MONTH=30
      IF (JKL.EQ.2) MONTH=28
      IF (GRCAL.GT.AMAX) AMAX=GRCAL
      AMONCL=GRCAL*MONTH
      TOTGRCL=TOTGRCL+AMONCL
40    CONTINUE
      EHS=TOTGRCL/AMAX
      WRITE(6,509) TOTGRCL,EHS
509   FORMAT('INSOLATION DURING ABLATION SEASON APR-SEPT = ',F10.2/
     1'EFFECTIVE HEATING SEASON = ',F5.1)
37    CONTINUE
      STOP
      END
```

APPENDIX 4 : PLATEAUX UPSLOPE FROM ROCK WALLS

Plateau Area (km^2)

Rock Wall	SE	SW	NW	NE	SOUTH	WEST
SE GRAMPIANS						
1	0.048	0.210	-	-	0.110	0.064
2	0.163	0.394	-	-	0.414	0.165
3	1.094	0.501	-	-	0.878	1.057
4	0.208	0.455	-	-	0.194	0.281
5	-	0.734	0.007	-	0.313	0.262
6	0.062	0.695	0.216	-	0.412	1.002
7	-	0.416	-	-	-	0.645
8	0.452	1.286	-	-	1.186	0.547
9	0.337	1.150	-	-	0.823	0.819
11	-	-	0.701	0.348	-	0.208
12	-	-	0.216	0.542	-	-
13	0.173	0.826	0.132	-	0.187	0.380
14	-	1.114	0.302	-	0.681	0.468
16	-	0.951	-	-	-	-
17	0.085	0.366	-	-	0.220	0.345
18	-	0.846	-	-	0.266	0.846
19	0.134	0.150	-	-	0.190	0.119
20	0.389	1.569	0.999	-	1.095	0.461
21	-	0.059	0.021	-	-	0.240
22	0.315	-	0.471	0.734	-	-
26	-	0.150	-	-	0.013	0.339
27	0.161	0.655	0.421	-	0.118	0.299
28	-	0.332	-	-	0.158	0.646
30	-	0.166	0.122	-	0.158	0.471
31	0.039	3.575	-	-	1.230	2.196
32	-	0.219	0.156	-	0.062	0.298
33	-	0.199	-	-	0.048	0.296

Rock Wall	SE	SW	NW	NE	SOUTH	WEST
34	0.085	-	0.682	0.531	-	0.289
35	0.005	-	0.730	0.707	-	0.144
36	-	-	0.869	0.358	-	0.153
37	0.849	0.768	0.081	-	1.768	0.370
40	-	0.684	-	-	0.333	0.287
41	-	0.276	-	-	0.077	0.547
42	0.100	0.726	-	-	0.156	-
44	-	0.071	0.008	-		
45	-	0.091	-	-		
46	0.004	0.114	-	-		
47	0.156	0.083	-	-		
48	0.137	0.066	-	-		
49	-	0.121	0.149	-		
50	-	0.047	0.007	-		
51	0.098	-	-	-		
52	-	0.012	0.100	0.019		
53	-	0.220	0.931	-	0.040	0.551
55	0.027	0.160	0.029	-	0.090	0.131
56	-	0.272	0.921	-	-	0.435
57	0.074	0.123	-	-	0.155	0.012
58	-	0.052	-	-	-	0.089
59	0.143	0.073	-	-	0.272	0.006
60	-	-	-	-	-	-
61	-	-	0.177	-	-	0.402
62	0.154	0.953	0.677	-	0.384	0.954
63	-	-	-	0.806	-	-
CAIRNGORMS						
65	0.222	0.189	-	-	0.204	0.051
66	1.211	0.256	-	-	1.499	0.018

Rock Wall	SE	SW	NW	NE	SOUTH	WEST
67	-	-	0.026	0.229	-	-
68	0.096	0.076	-	-	0.139	0.008
314	0.511	1.596	0.134	-	1.130	0.973
315	-	0.336	0.175	-	0.155	0.582
316	0.600	0.037	-	-	0.671	-
317	0.645	0.025	-	-	0.338	-
318	0.160	0.214	0.422	-	0.119	0.343
320	-	0.280	0.762	0.139	0.014	0.660
321	0.736	0.045	-	-	0.429	-
322	-	0.107	-	-	0.030	0.130
323	0.071	0.022	-	-	0.097	0.023
324	-	0.001	-	-	-	-
325	0.004	0.169	-	-	0.067	0.046
326	-	0.117	-	-	0.011	0.102
327	-	0.313	0.315	-	0.072	0.519
328	-	-	-	0.121	-	-
329	0.377	0.324	-	-	0.456	0.474
330	0.468	0.605	-	-	1.048	0.026
331	0.172	0.101	-	-	0.332	0.041
332	-	0.067	-	-	0.069	0.018
333	0.098	0.152	-	-	0.106	0.048
334	-	0.112	0.011	-	-	0.150
335	-	0.082	-	-	0.011	0.069
336	-	0.394	0.157	-	0.093	0.520
337	-	0.377	0.137	-	0.091	0.560
338	-	0.167	0.081	-	0.004	0.324
339	-	0.019	0.061	-	-	0.118
340	-	0.119	0.412	-	0.036	0.723
341	-	0.329	1.371	-	0.217	0.772
342	-	0.309	0.597	-	0.176	0.280
343	-	0.579	0.790	-	0.306	1.018

Rock Wall	SE	SW	NW	NE	SOUTH	WEST
344	0.105	0.539	0.242	-	0.428	0.219
345	-	-	0.206	-	-	0.062
346	0.337	0.221	-	0.012	0.600	0.005
347	0.884	0.069	-	0.075	0.499	-
348	0.532	0.960	0.266	-	0.117	0.624
350	0.529	0.026	-	0.071	0.265	-
351	0.327	0.286	-	0.029	0.531	0.067
352	-	0.398	0.353	-	0.080	0.463
353	-	0.171	0.387	0.626	0.129	0.229
354	0.286	0.364	-	-	0.904	0.240
355	-	0.441	0.323	-	0.553	0.176
356	0.282	0.348	-	-	0.507	-
357	-	0.296	0.548	-	0.111	0.534
WEST HIGHLANDS						
161	0.063	0.007	-	-		
162	0.021	0.002	-	-		
163	-	-	-	-		
164	0.012	0.016	-	-		
165	-	0.044	-	-		
166	-	-	-	-		
167	-	-	-	-		
168	-	0.010	-	-		
169	-	-	-	-		
170	-	0.031	0.009	-		
171	-	0.011	0.000	-		
172	-	-	-	-		
173	0.101	0.015	-	-		
174	-	-	-	-		

Rock Wall	SE	SW	NW	NE
175	-	-	-	-
176	0.052	0.008	-	-
178	0.007	-	-	-
180	-	-	-	-
181	-	-	-	-
182	0.013	0.027	-	-
183	-	-	-	-
184	0.076	-	-	-
185	-	-	-	-
186	-	0.011	-	-
187	-	-	-	-
188	-	0.003	-	-
189	0.004	0.019	-	-
190	0.126	0.039	-	-
191	0.009	0.001	-	-
192	-	0.004	-	-
193	-	0.027	-	-
194	-	-	-	-
196	-	-	-	-
198	-	0.055	-	-
199	-	-	-	-
200	-	-	-	-
201	0.001	0.034	-	-
202	-	-	-	-
203	-	-	-	-
204	-	-	-	-
205	-	-	-	-
206	-	0.076	-	-
207	-	-	-	-
208	-	-	-	-
209	0.004	-	-	0.032
210	0.140	0.113	-	-

Rock Wall	SE	SW	NW	NE
211	-	-	-	-
212	-	-	-	-
213	-	-	-	-
214	-	-	-	-
215	-	0.144	-	-
216	0.031	0.205	-	-
217	0.056	0.016	-	-
218	0.054	0.061	-	-
219	-	-	-	-
220	-	-	-	-
221	-	-	-	-
222	-	-	-	-
223	-	-	-	-
224	-	-	-	-
225	0.010	0.109	-	-
226	0.124	-	-	0.143
227	-	-	-	-
228	0.017	0.169	-	-
229	0.009	0.008	-	-
230	0.004	0.021	-	-
231	-	0.039	-	-
232	0.001	-	-	-
233	-	0.010	-	-
234	-	-	-	-
235	-	-	-	-
236	-	0.234	0.042	-
237	0.015	0.043	-	-
238	0.012	0.034	-	-
239	0.019	-	-	-
240	-	0.011	-	-

Rock Wall	SE	SW	NW	NE
241	0.076	0.025	-	-
243	0.004	0.093	-	-
244	-	0.263	-	-
245	-	-	-	-
246	0.089	0.259	-	-
247	0.049	0.049	-	-
248	0.035	0.024	-	-
250	0.026	-	-	-
252	0.029	-	-	-
253	-	-	-	-
254	0.024	0.016	-	-
255	-	-	-	-
256	-	-	-	-
257	-	-	-	-
258	-	-	-	-
259	-	-	-	-
260	-	-	-	-
261	-	-	-	-
262	-	-	-	-
263	-	-	-	-
264	-	-	-	-
265	-	-	-	-
266	-	-	-	-
267	-	-	-	-
268	0.027	-	-	-
269	0.004	0.009	-	-
270	0.286	0.081	-	-
271	-	0.050	-	-
272	0.093	0.009	-	-

Rock Wall	SE	SW	NW	NE
273	0.049	-	-	-
274	-	-	-	-
275	-	-	-	-
276	-	-	-	-
277	0.046	0.083	-	-
278	-	0.054	-	-
279	-	0.061	-	-
280	-	0.039	0.022	-
281	0.089	0.042	-	-
282	-	0.025	-	-
283	0.084	-	-	-
284	0.137	0.029	-	-
285	-	-	-	-
286	-	-	-	-
288	-	0.021	-	-
289	-	-	-	-
290	-	-	-	-
291	0.004	0.037	-	-
292	-	0.198	-	-
293	-	0.113	-	-
294	-	-	-	-
295	-	-	-	-
296	-	-	-	-
297	0.037	0.073	-	-
298	0.235	0.220	-	-
299	-	-	-	-
300	-	-	-	-
301	-	-	-	-
302	-	-	-	-
303	-	-	-	-
304	-	-	-	-

Rock Wall	SE	SW	NW	NE
305	-	-	-	-
306	-	-	-	-
307	-	-	-	-
308	-	-	-	-
309	-	-	-	-
310	-	0.003	0.093	-
311	-	-	-	-
312	-	-	-	-
313	-	0.031	-	-
484	-	-	-	-
485	-	0.053	0.036	-
486	-	-	-	-
487	-	-	-	-
511	0.201	0.194	-	-
512	0.300	0.201	-	-
513	0.341	0.201	-	-
514	-	-	-	-
515	-	0.055	0.020	-
516	-	0.014	0.106	-
517	-	-	-	0.182
518	-	0.200	0.105	-
519	-	-	-	-
SW GRAMPIANS				
74	-	0.129	0.008	-
78	0.010	-	-	0.406
79	-	0.116	-	-
81	1.469	-	-	-
83	-	0.261	-	-
84	-	0.152	-	-
85	0.061	-	-	-
82	-	0.036	-	-

Rock Wall	SE	SW	NW	NE
86	-	0.275	0.226	-
87	-	0.086	-	-
88	0.536	0.241	-	-
89	0.285	0.144	-	-
90	0.146	0.046	-	-
91	-	0.136	-	-
92	-	0.091	-	-
93	0.036	0.141	-	-
94	-	-	-	-
95	-	0.068	-	-
96	-	-	-	-
97	-	-	-	-
98	0.101	0.081	-	-
99	0.114	0.415	-	-
100	0.157	0.219	-	-
101	-	0.094	0.040	-
102	-	0.321	-	-
103	0.111	0.048	-	-
104	-	0.009	-	-
106	-	-	0.010	-
107	0.032	0.210	-	-
109	0.161	-	0.564	-
111	-	0.548	-	-
112	-	0.387	-	-
113	-	0.194	-	-
114	0.016	0.532	-	-
115	-	-	2.274	-
121	0.008	0.032	-	-
414	0.242	-	-	0.403
415	-	0.242	-	-

Rock Wall	SE	SW	NW	NE
416	0.008	0.032	-	-
417	-	-	-	-
418	-	-	-	-
419	-	0.081	0.161	-
420	-	0.005	-	-
421	-	-	0.048	-
422	-	0.145	-	-
423	-	0.065	0.032	-
424	-	-	-	-
425	-	-	-	-
426	-	0.113	-	-
427	-	-	-	-
428	-	0.011	0.011	-
429	-	-	-	-
430	0.015	0.016	0.001	-
431	0.007	0.018	-	-
432	-	0.139	0.002	-
433	-	-	-	-
434	-	-	-	-
435	-	-	-	-
436	-	-	-	-
437	-	-	-	-
438	-	0.020	-	-
439	-	-	0.013	-
440	-	0.099	-	-
441	-	0.013	0.001	-
442	-	-	0.007	-
443	-	0.100	0.045	-
444	-	-	-	-
445	-	0.084	-	-
446	-	0.051	0.009	-
447	-	0.069	0.156	0.045

Rock Wall	SE	SW	NW	NE
448	0.015	0.074	-	-
453	-	-	-	-
456	-	-	-	-
457	0.018	0.040	-	-
458	-	-	-	-
459	-	-	-	-
460	-	-	-	-
461	-	-	-	-
462	-	-	-	-
463	-	-	-	-
464	-	-	-	-
465	-	-	-	-
466	0.145	-	-	-
467	-	-	-	-
468	-	-	-	-
469	0.032	-	-	-
470	-	-	-	-
471	0.226	-	-	-
472	-	0.113	-	-
473	-	-	-	-
474	-	-	-	-
475	-	-	0.008	-
476	-	-	-	-
477	-	-	0.219	-
MONADHLIATH REGION				
120	-	0.403	1.452	0.113
124	-	0.006	-	-
125	-	1.403	-	-
126	0.032	0.081	-	-
127	-	0.097	0.355	-

Rock Walls	SE	SW	NW	NE
450	0.048	0.102	-	-
454	-	0.016	0.032	-
455	0.193	1.290	-	-
SKYE				
358	-	-	-	-
359	-	-	-	-
360	-	-	-	-
361	-	-	-	-
362	-	-	-	-
363	-	-	-	-
364	0.070	-	-	-
365	-	-	-	-
366	-	-	-	-
367	0.035	-	-	-
368	-	-	-	-
369	-	-	-	-
370	-	-	-	-
371	-	-	-	-
372	-	-	-	-
373	-	-	-	-
374	-	-	-	-
375	-	-	-	-
376	-	-	-	-
377	-	-	-	-
378	-	-	-	-
379	-	-	-	-
380	-	-	-	-
381	-	-	-	-
382	-	-	-	-

Rock Wall	SE	SW	NW	NE
128	-	-	0.048	-
129	0.274	0.290	-	-
130	0.129	0.008	-	-
131	-	-	0.242	0.145
132	-	0.484	0.011	-
133	1.129	0.339	-	-
134	-	0.177	-	-
135	0.129	0.290	-	-
136	-	0.204	0.117	0.029
137	-	0.131	0.035	-
138	-	0.148	-	-
139	0.041	-	-	-
140	0.741	0.369	-	-
141	-	-	-	-
142	0.031	0.317	-	-
143	-	0.103	0.119	-
144	-	0.719	-	-
146	-	-	0.713	-
148	-	-	-	0.046
149	-	0.021	-	-
150	-	0.001	0.037	-
153	-	0.086	0.032	-
154	0.048	0.102	-	-
155	-	-	0.030	-
156	-	0.026	0.199	0.009
157	-	0.002	0.129	-
158	-	0.005	0.011	-
159	-	0.033	-	-
160	-	0.068	-	-
449	0.151	0.394	-	-

Rock Wall	SE	SW	NW	NE
383	-	-	-	-
384	-	-	-	-
385	-	-	-	-
386	-	-	-	-
387	-	-	-	-
388	-	-	-	-
389	-	-	-	-
390	-	-	-	-
391	-	-	-	-
392	-	-	-	-
393	-	-	-	-
394	-	-	-	-
395	-	-	-	-
396	-	0.021	-	-
397	-	0.043	-	-
398	-	0.141	-	-
399	-	-	-	-
400	-	-	-	-
401	-	-	-	-
402	-	-	-	-
403	-	-	-	-